CMS HF measurements and implication to sPHENIX studies

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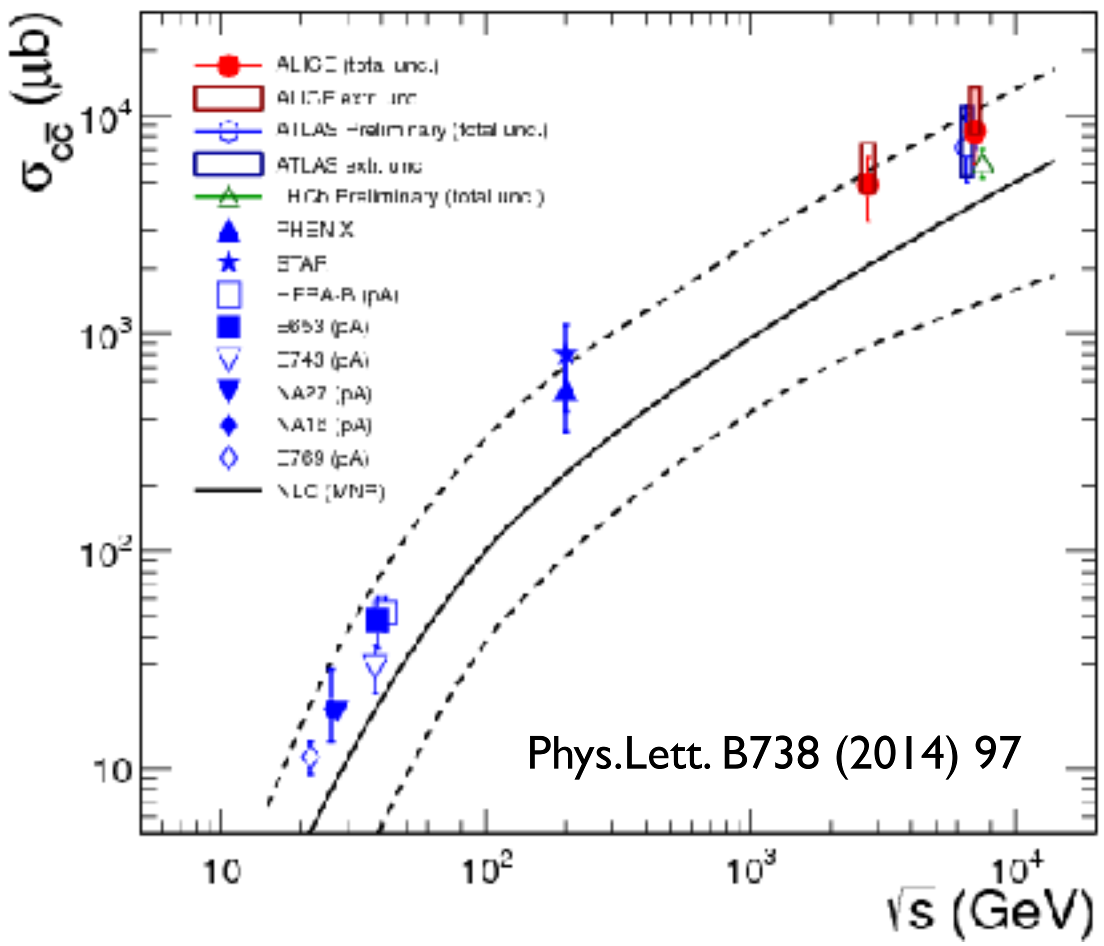
Brainstorming meeting for MVTX detector physics deliverable

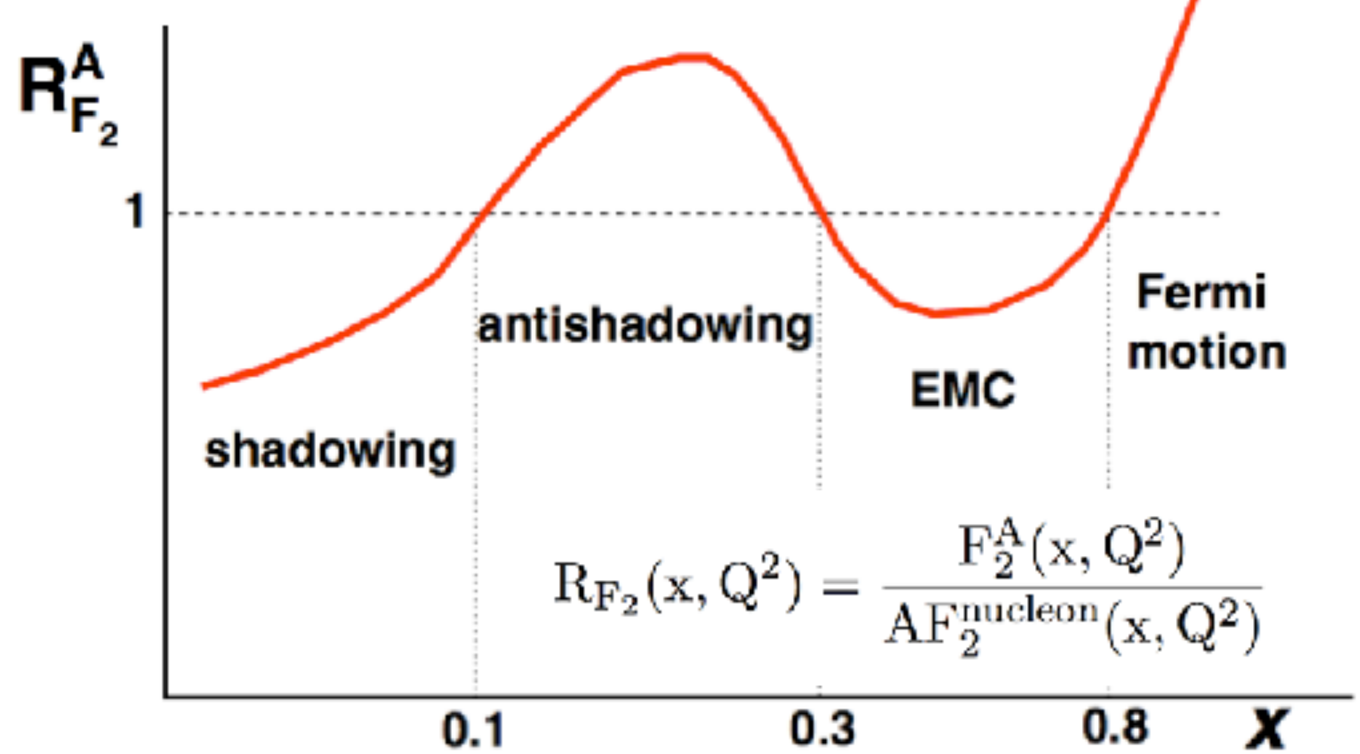
Introduction to heavy flavour physics

Heavy quarks produced in high Q^2 processes at early stages of the collisions



pp:
- test of pQCD calculations
- reference for pA and AA measurements
- role of MPI interactions

N. Armesto, arXiv:hep-ph/0604108v2.

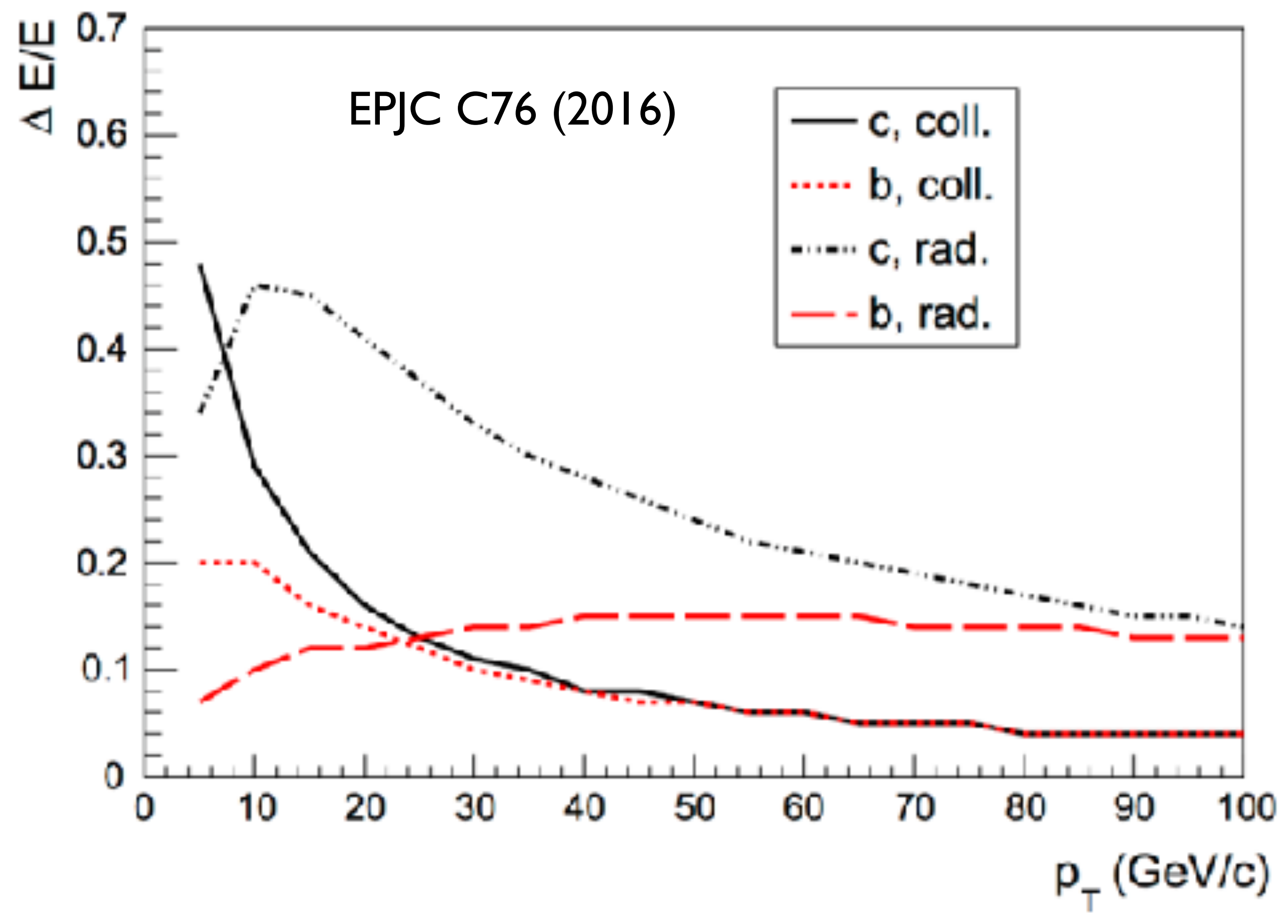


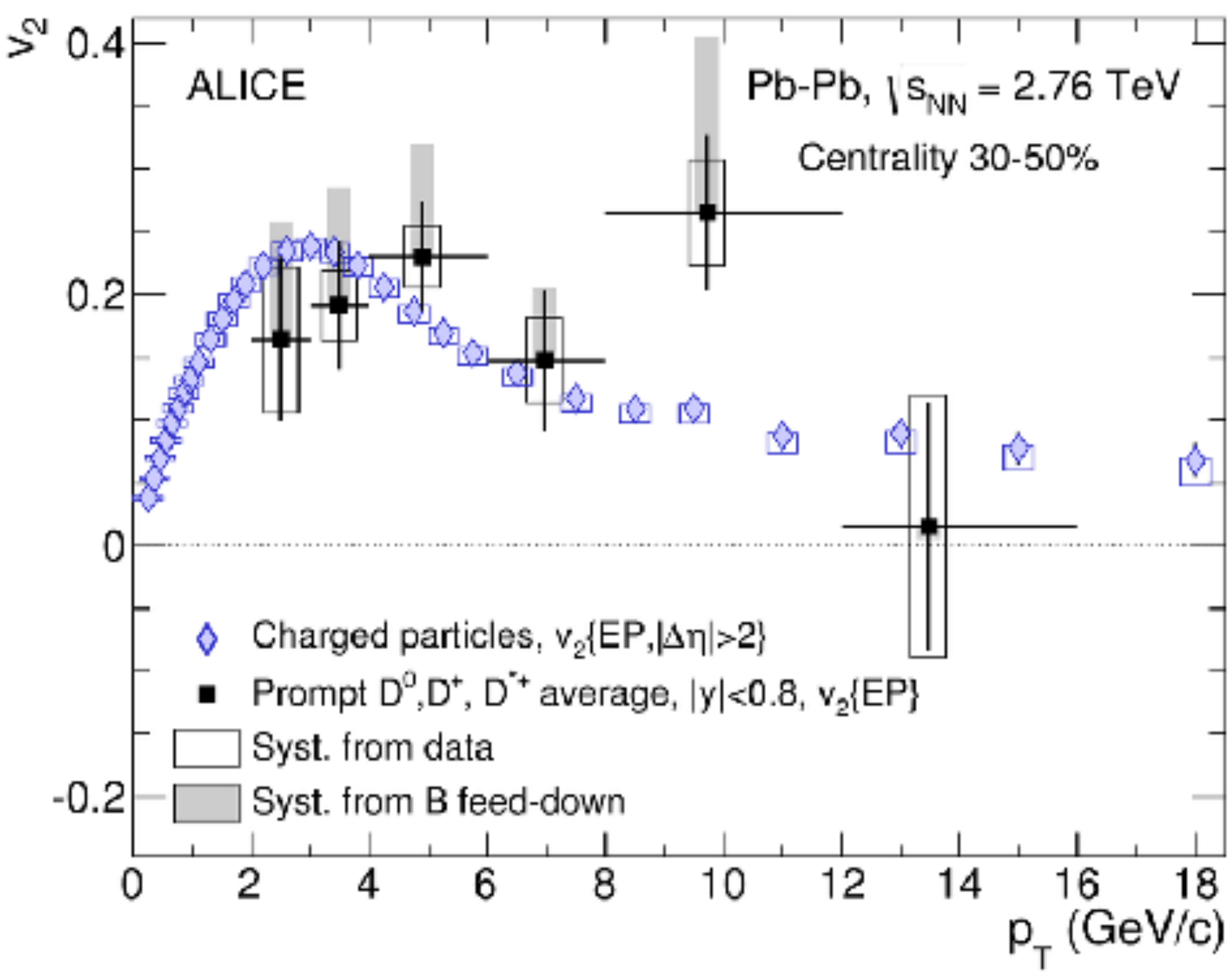
pPb:
- test of cold nuclear matter effects
  - PDF modifications
  - saturation
  - final state effects
- collective evolution (hydro?)

Introduction to heavy flavour physics

Heavy quark energy loss in PbPb:
- **collisional** vs **radiative** component

Flavour dependence energy loss:
- $\langle \Delta E \rangle \propto \alpha_s C_R q L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks

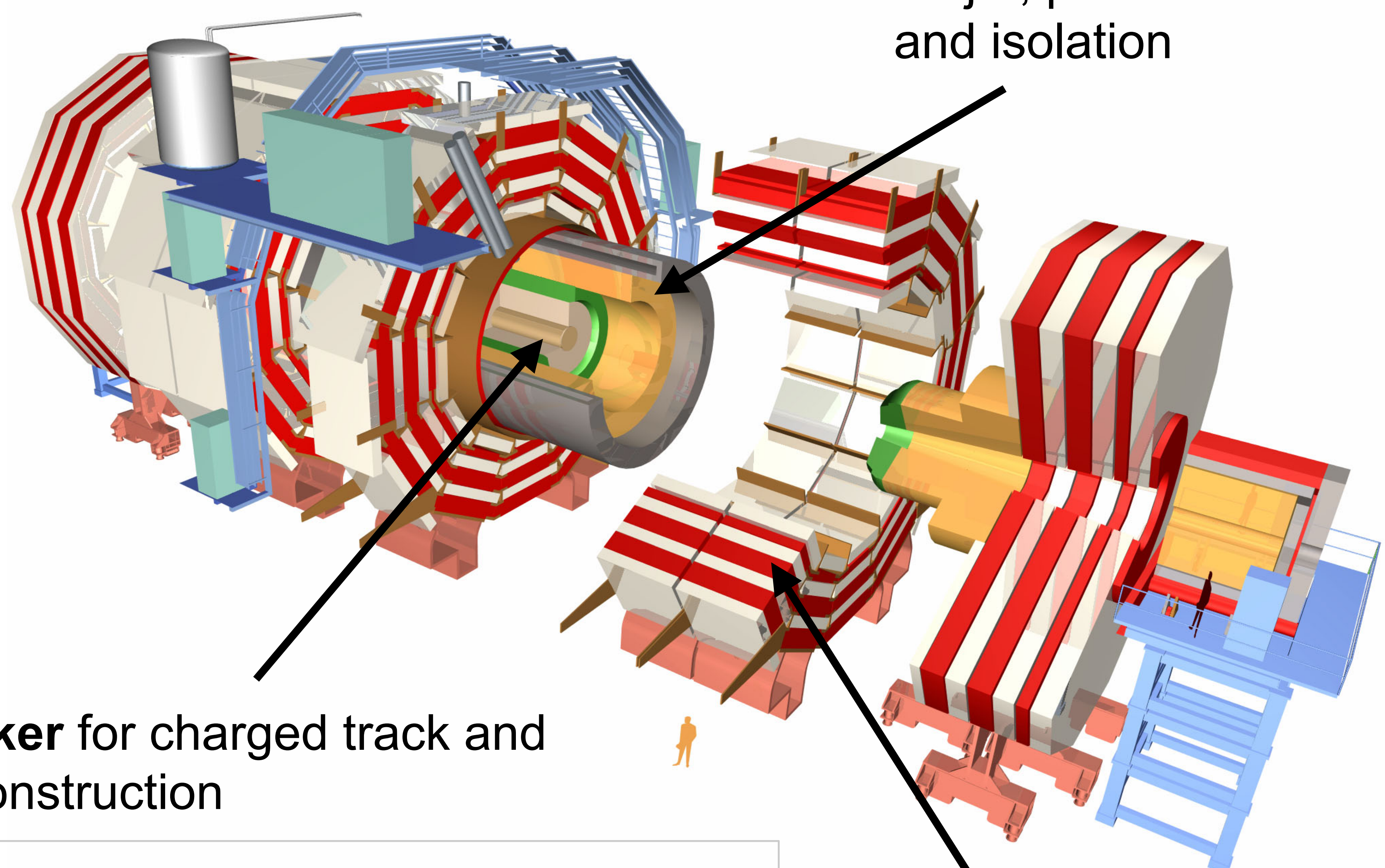




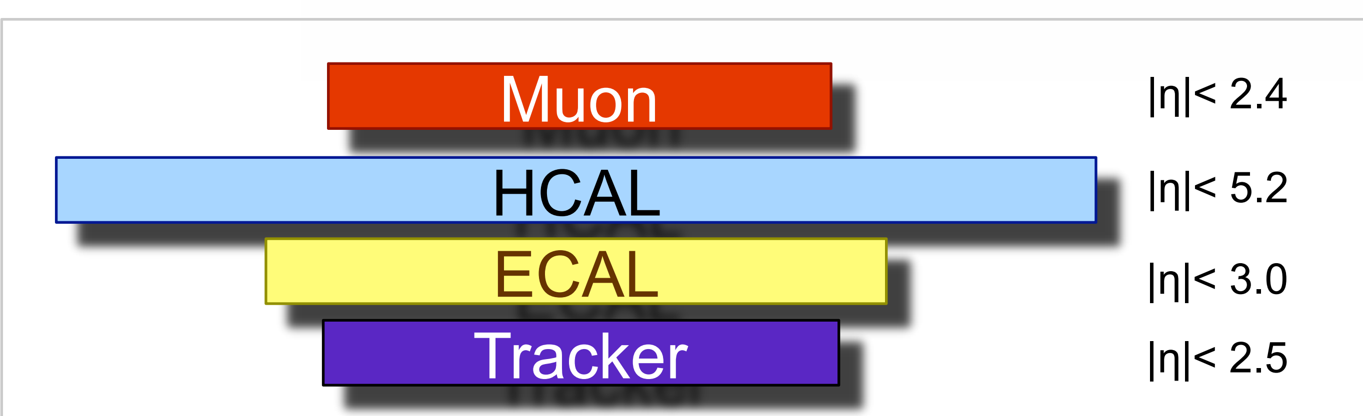
Collective behaviour:
- v_n measurements to study collective behaviour of heavy quarks
- charm recombination in medium?

Overview of the CMS detector

EM and hadron calorimeters for jet, photon reconstruction and isolation

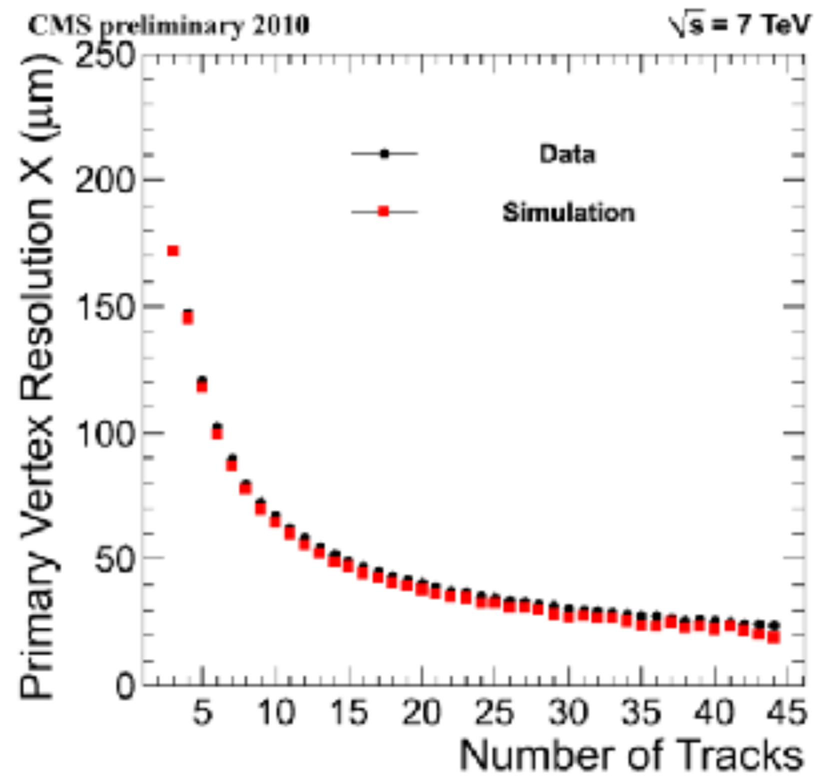


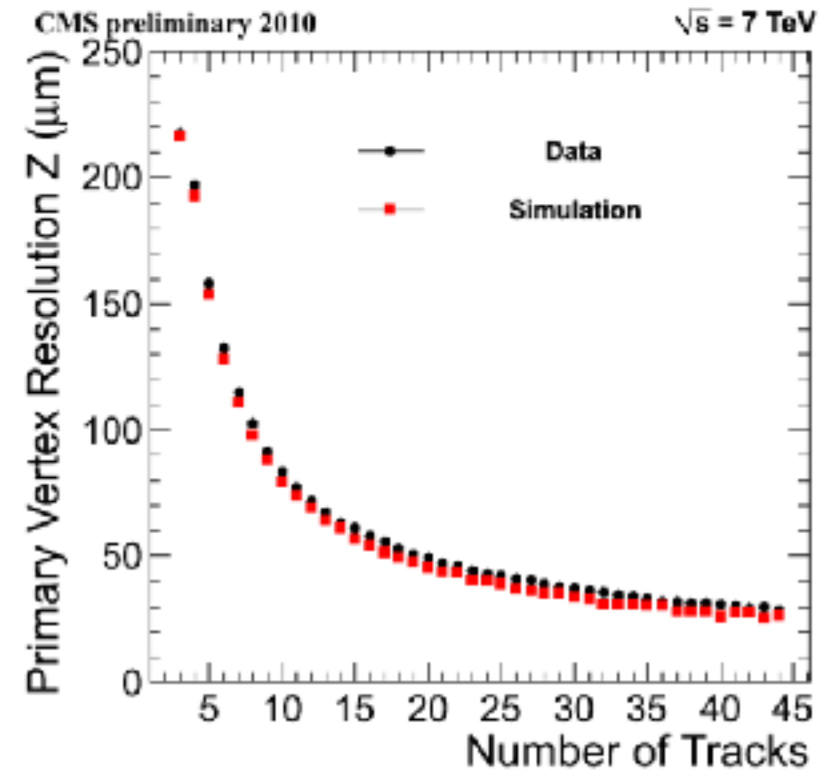
Inner tracker for charged track and vertex reconstruction

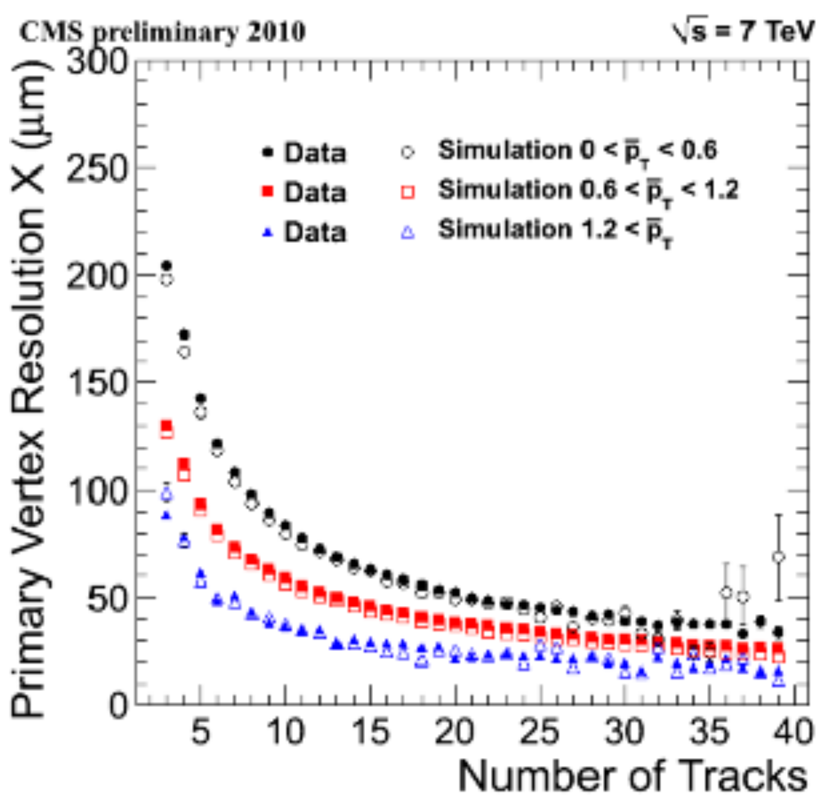


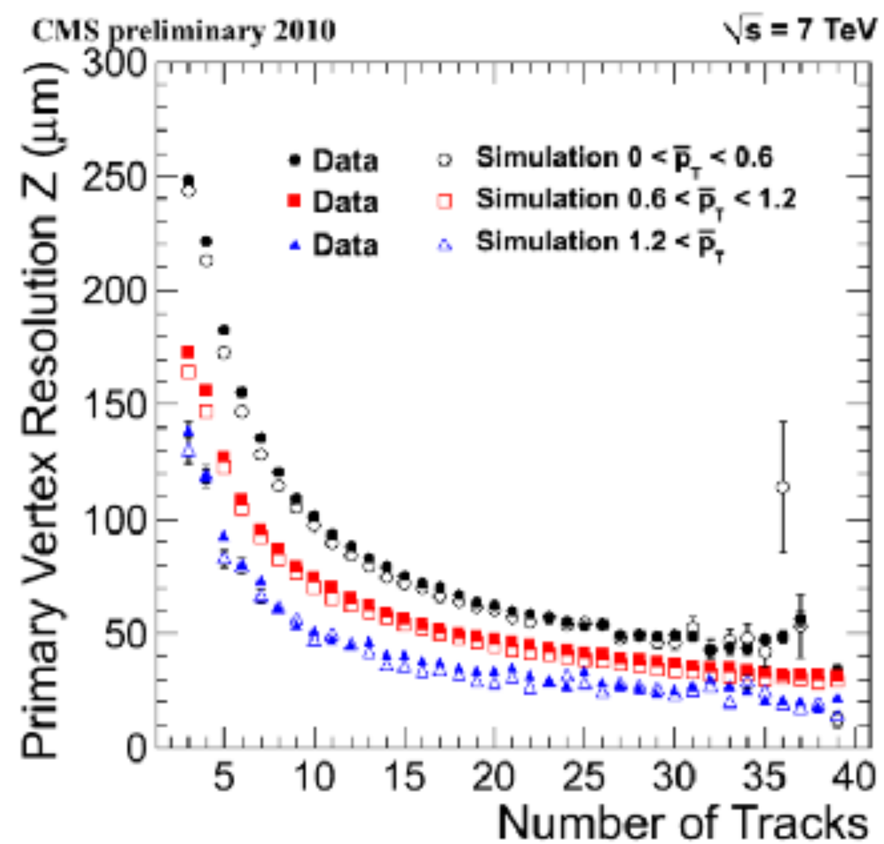
Muon system for muon reconstruction and triggering

Primary vertex resolution in pp collisions



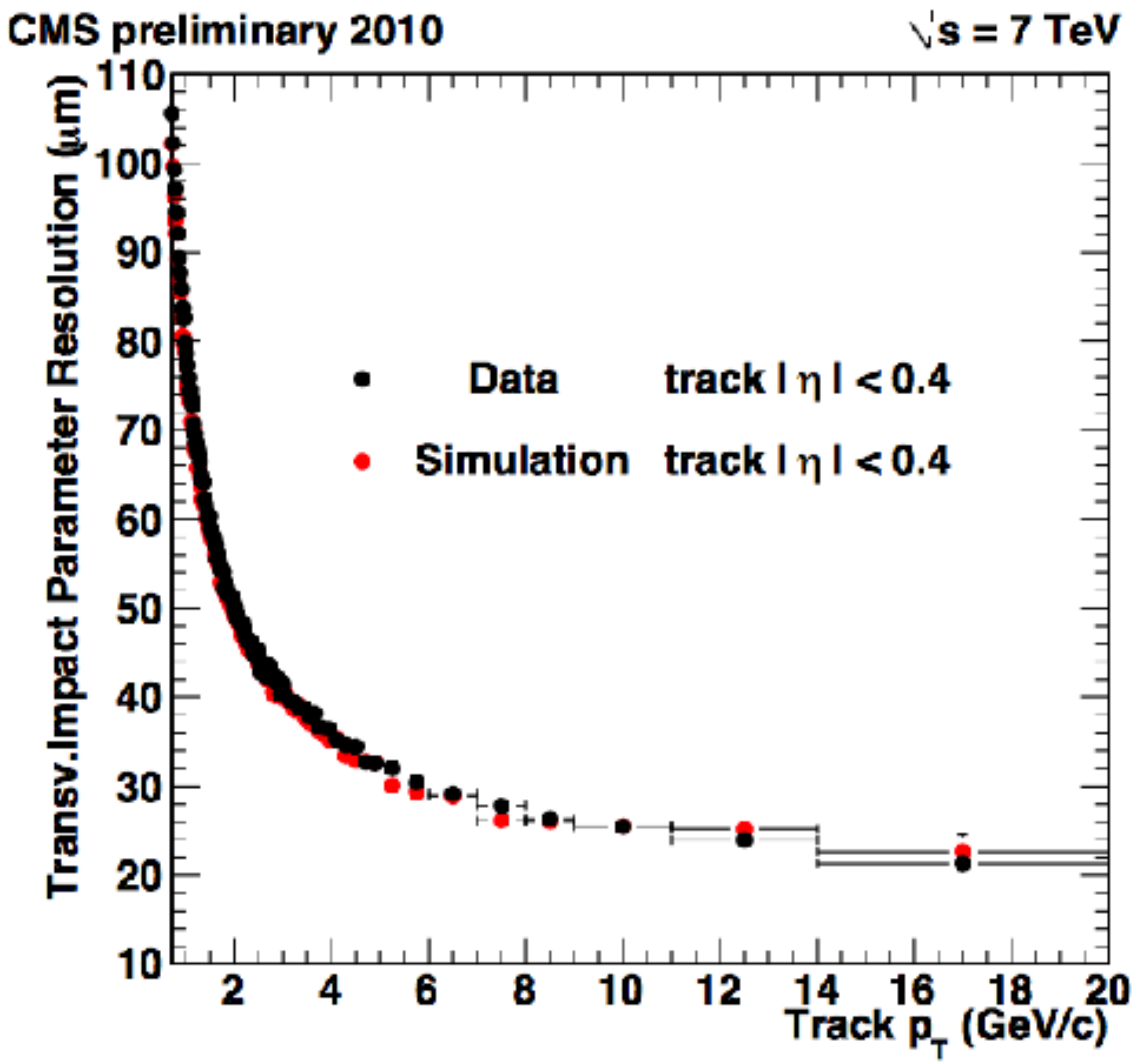


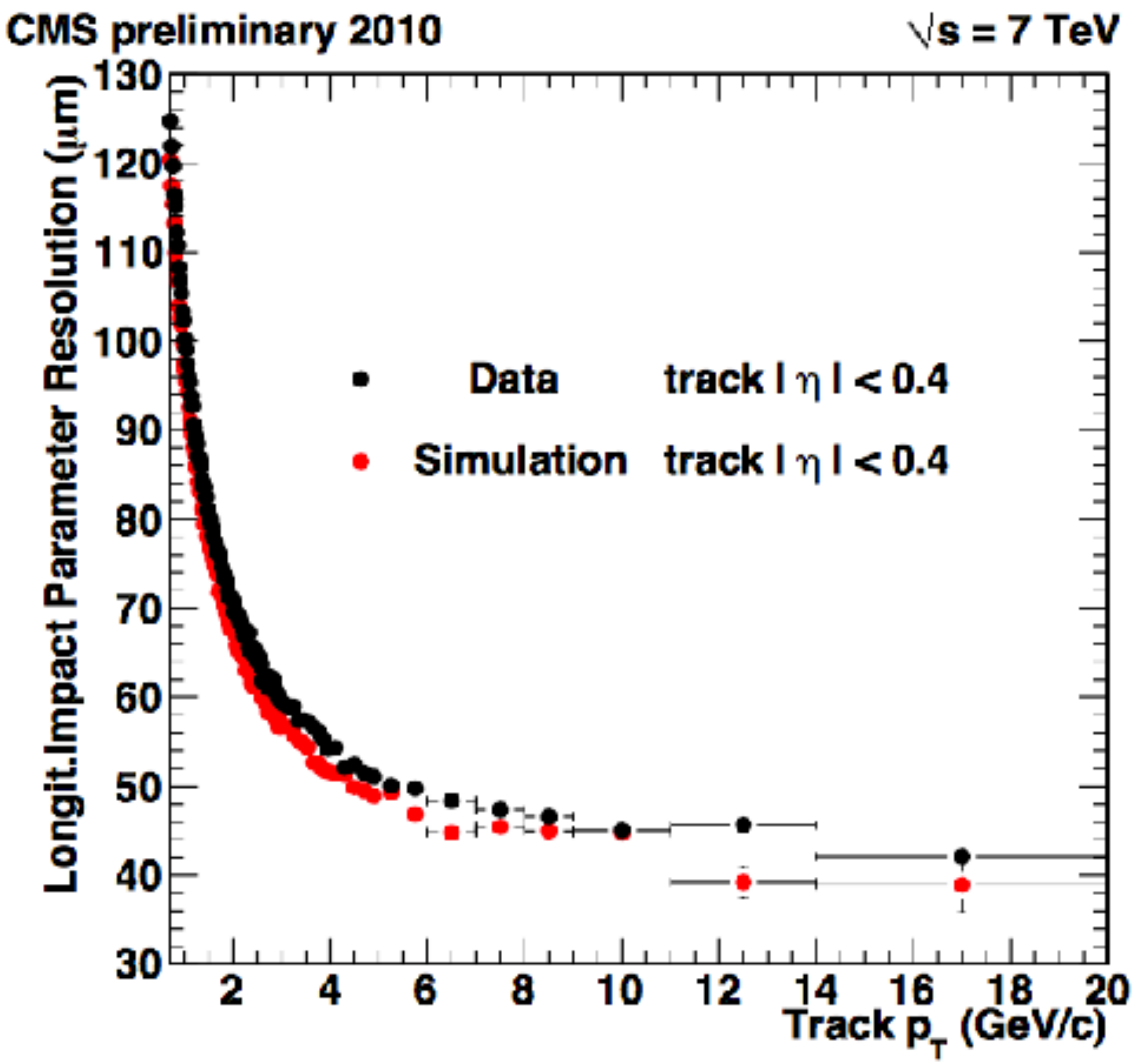




https://arxiv.org/pdf/1405.6569.pdf

Impact parameter resolution in pp collisions





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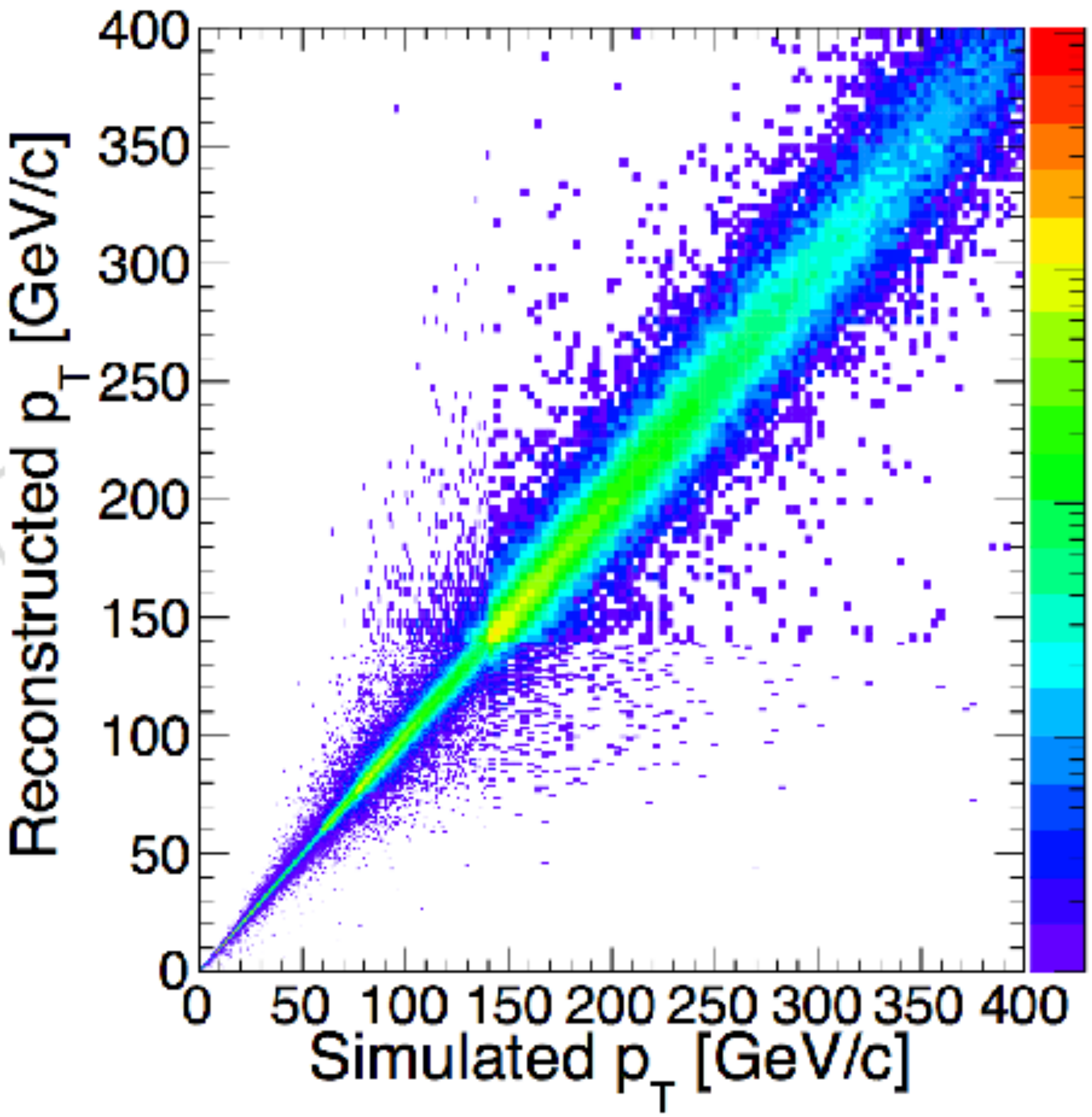
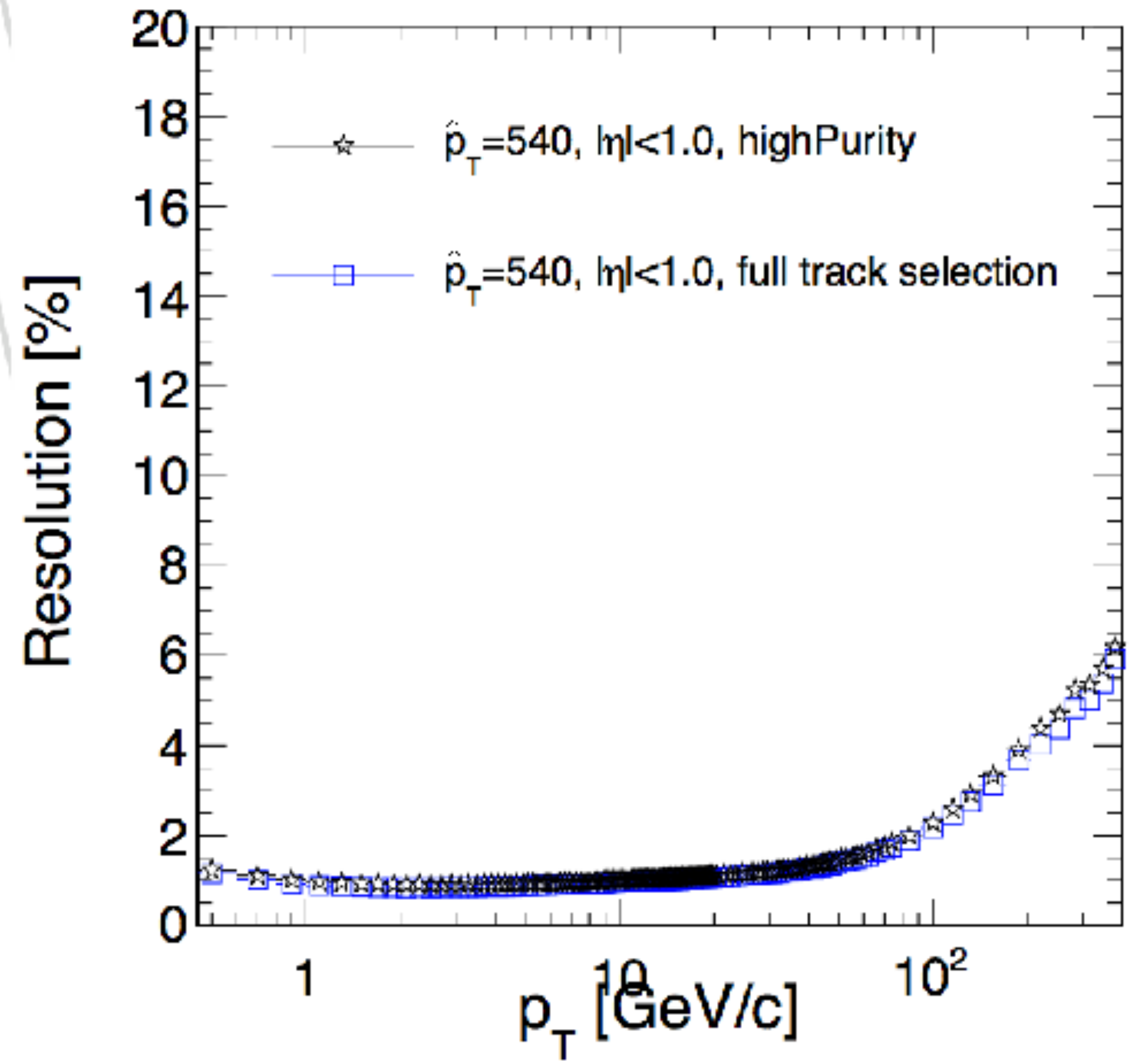
p_T resolution in PbPb collisions at 5 TeV





key features for a successful HF experiment

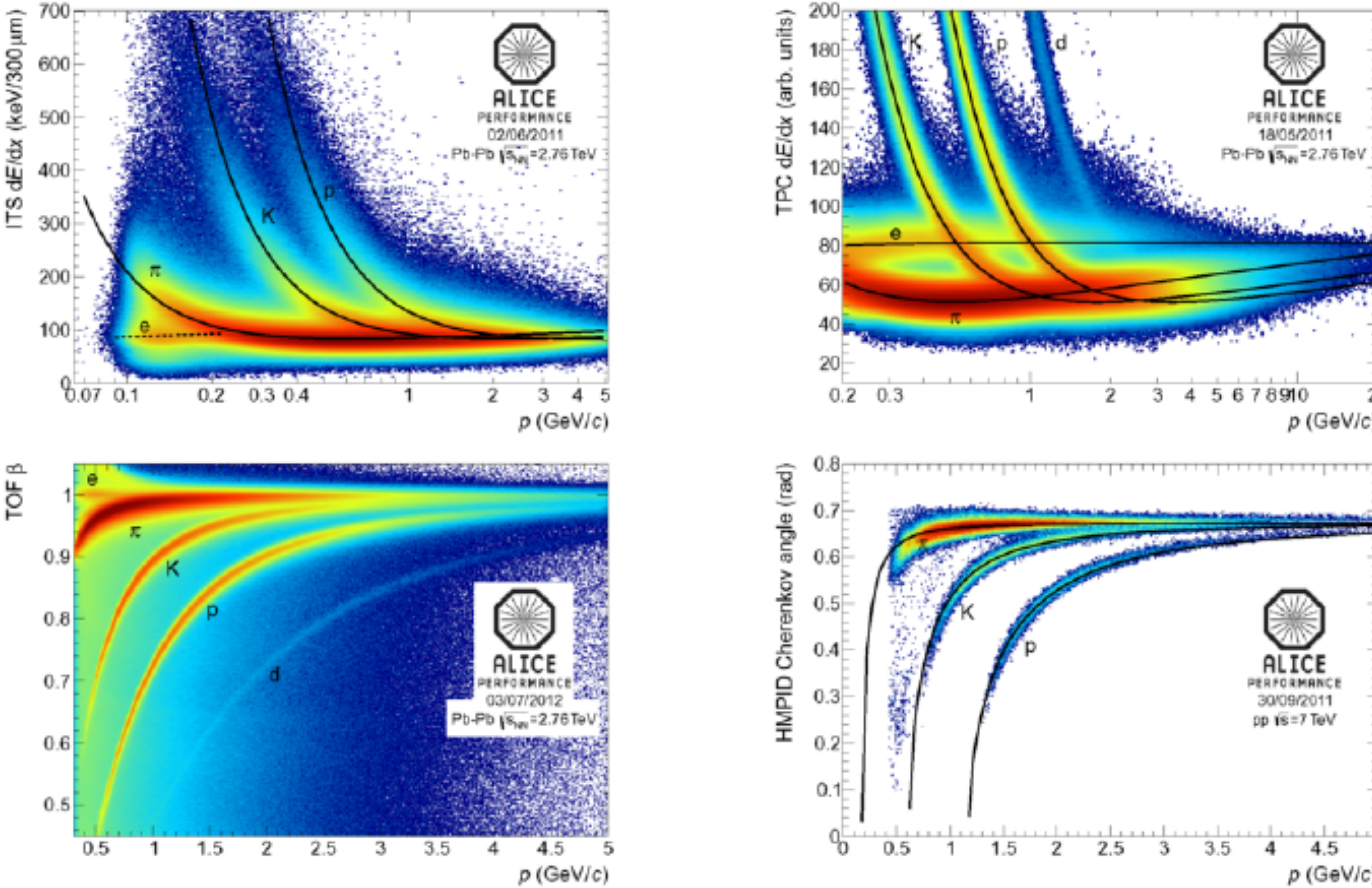
From our experience with CMS and LHC it is fundamental to have:

- primary and secondary vertex resolution
- good impact parameter resolution down to low p_T

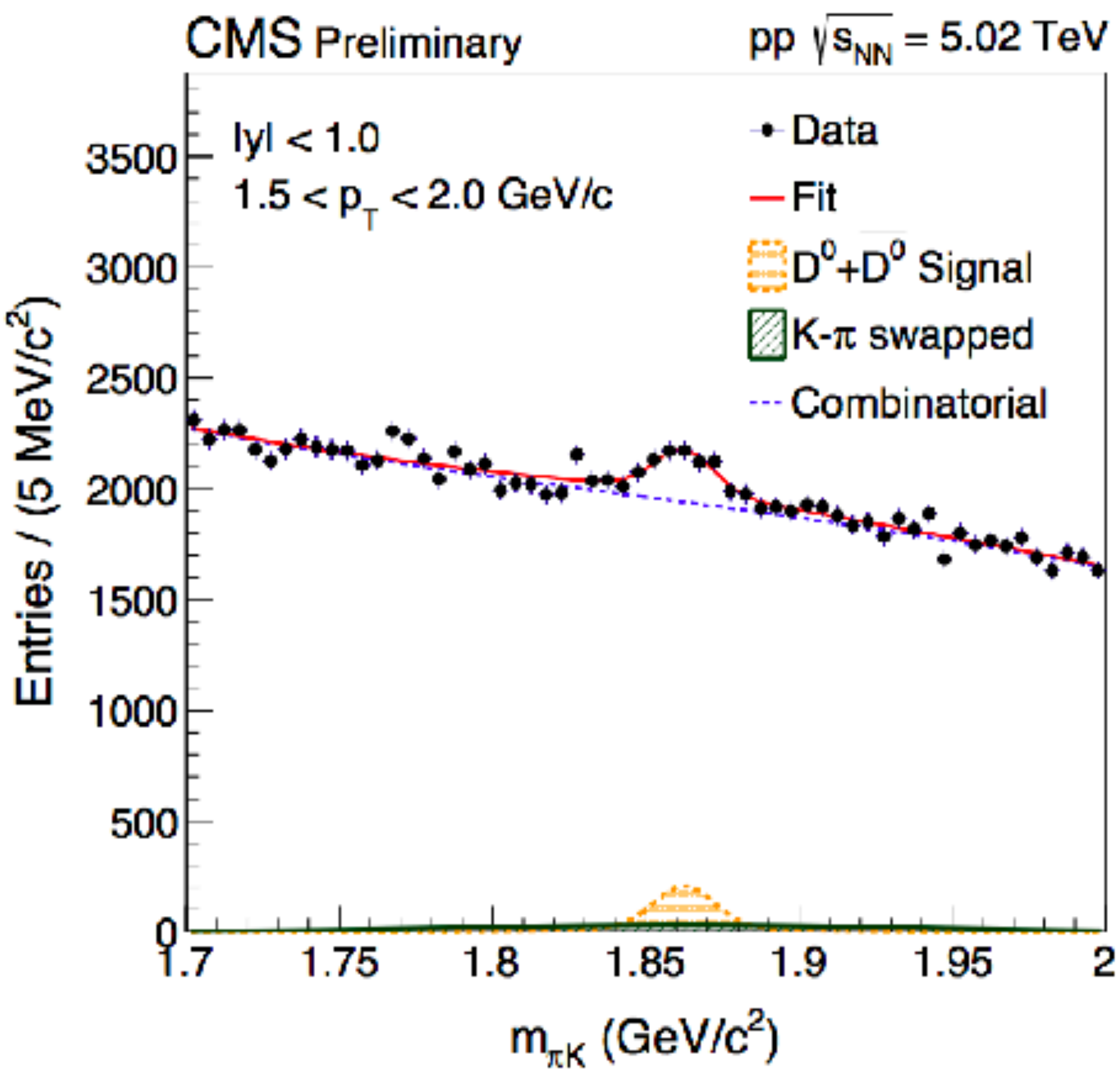
- **Is PID fundamental for low p_T D mesons?** CMS low pt results demonstrated that PID is important but is not strictly necessary

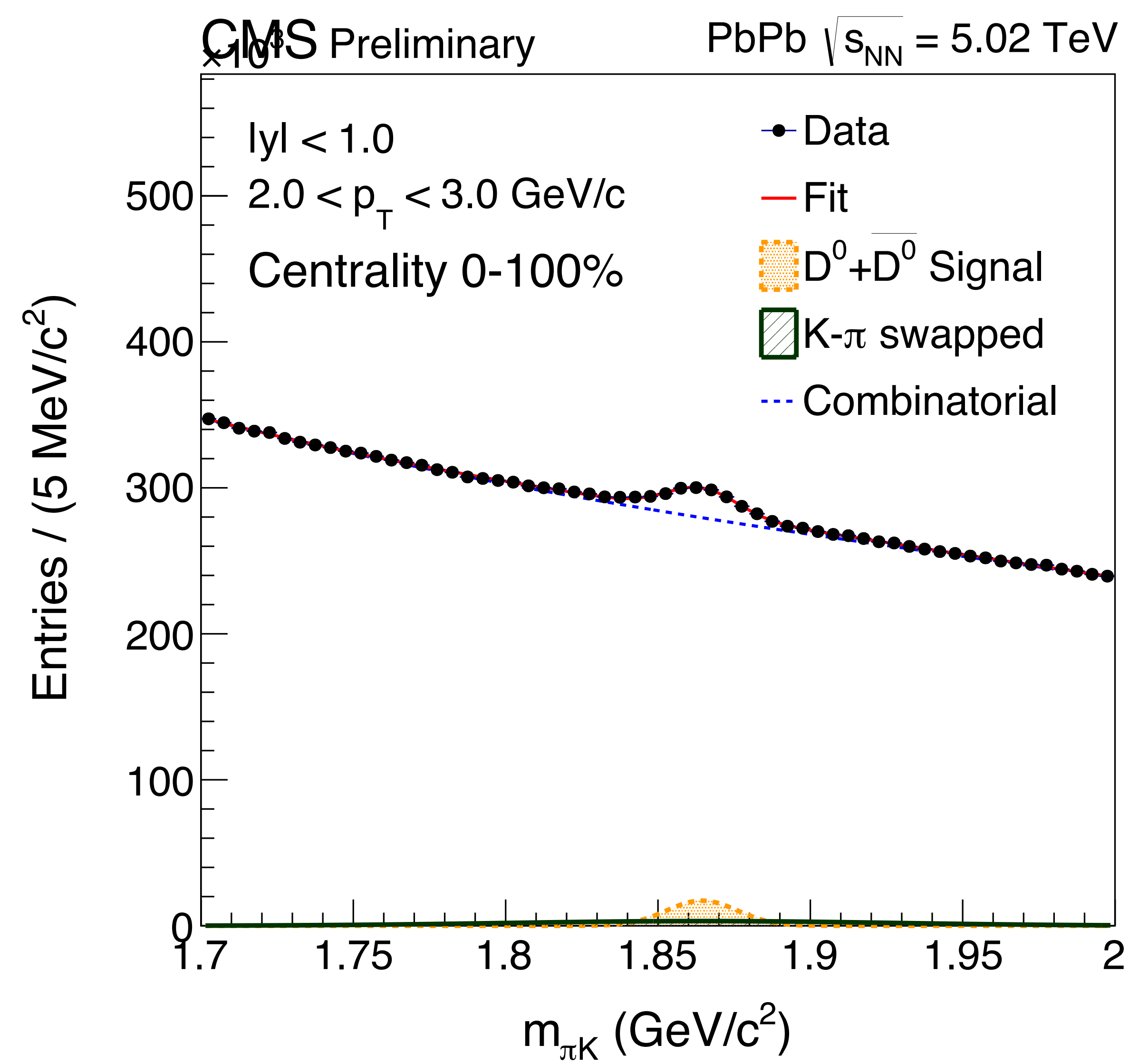
- **For low p_T physics, very big MB samples are clearly more important as shown by the comparison between CMS and ALICE results…**

PID ALICE performances ITS/TPC/TOF



CMS low p_T results without PID

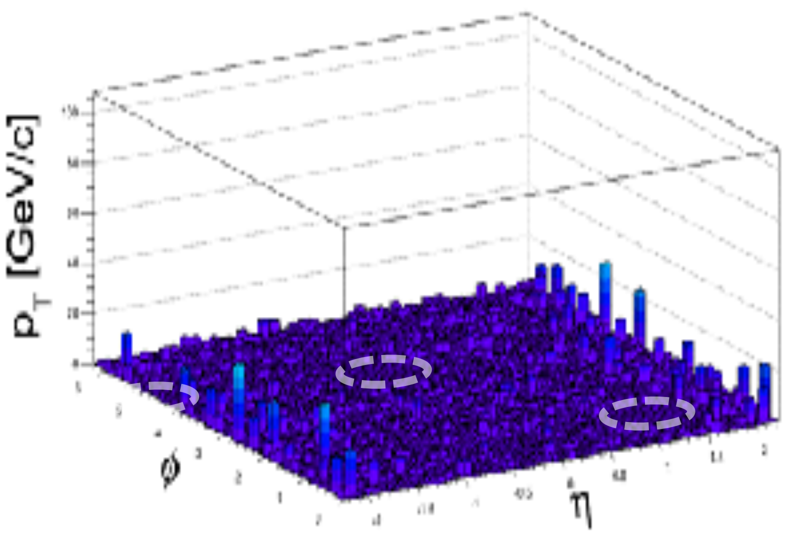


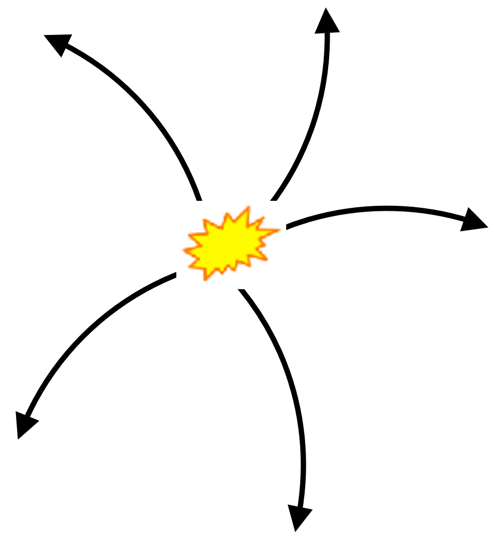


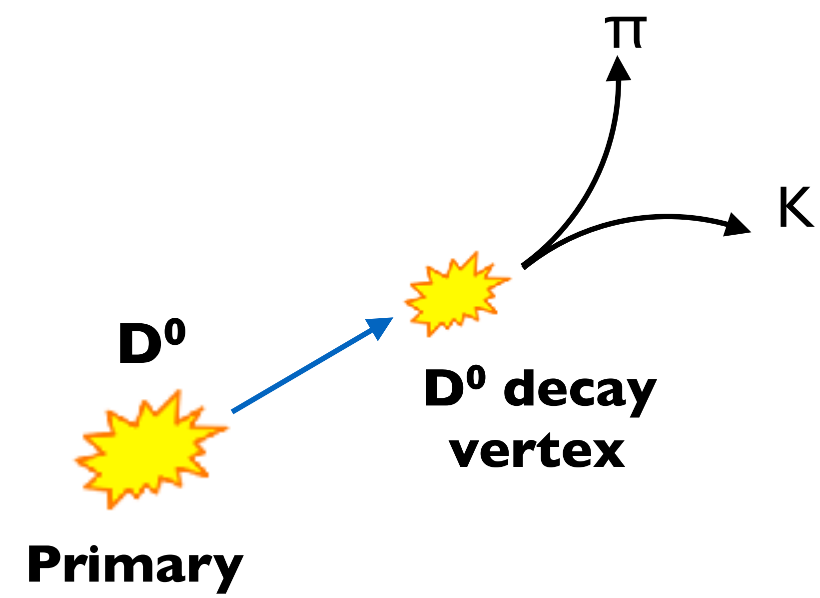
With very large samples (**~2.5 billion MB events in pp and ~300M events in 0-100% PbPb**) we can go down to very low p_T.

We can actually do better (down to 1 GeV or lower) with more cut optimisation (machine learning techniques…)

D^0 triggers at High-Level-Trigger (HLT)







Events firing hardware jet triggers (Level-1) are selected

- L1 jet algorithm with online background subtraction

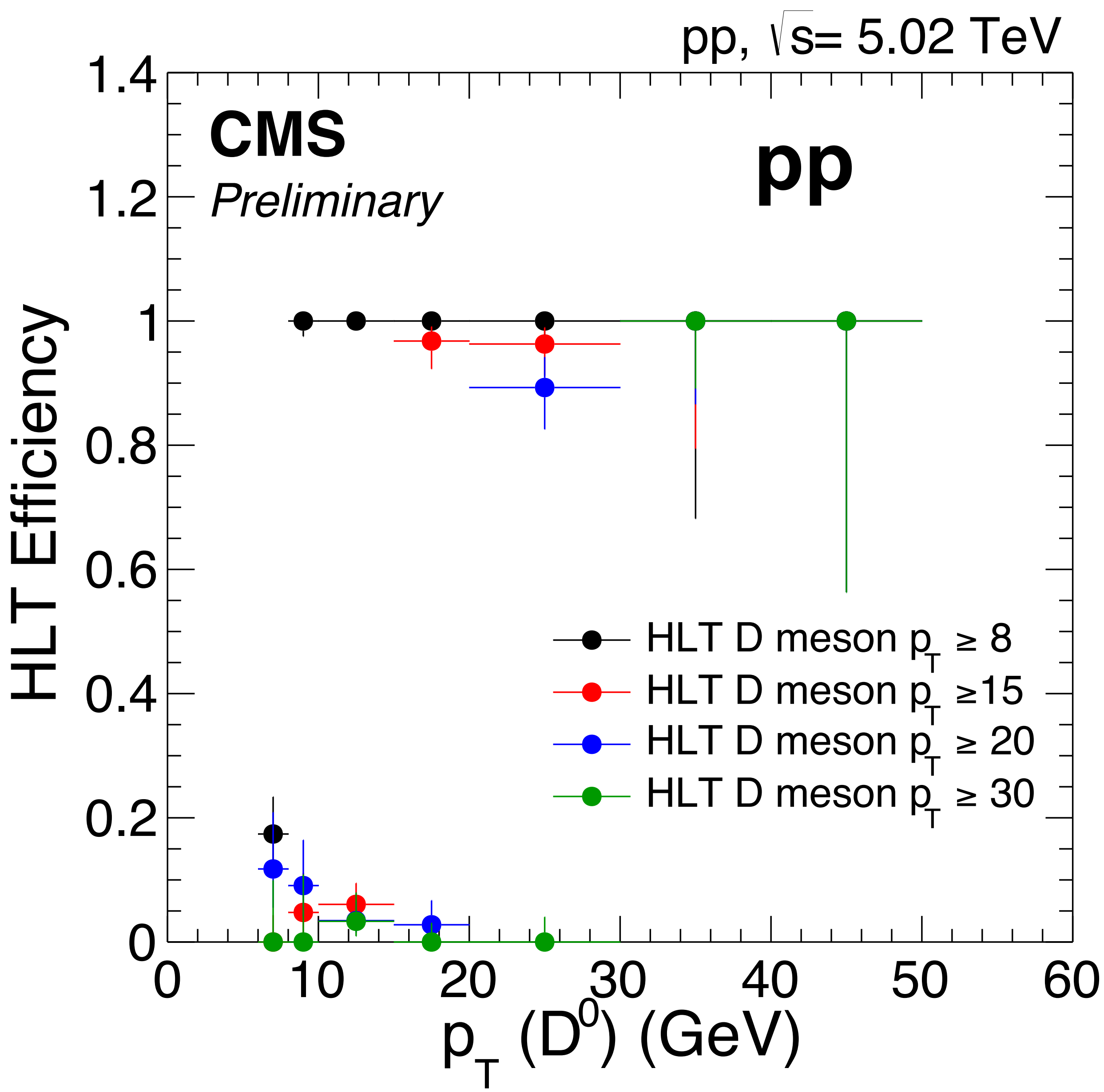
Tracks are reconstructed in software trigger system (HLT) for selected events

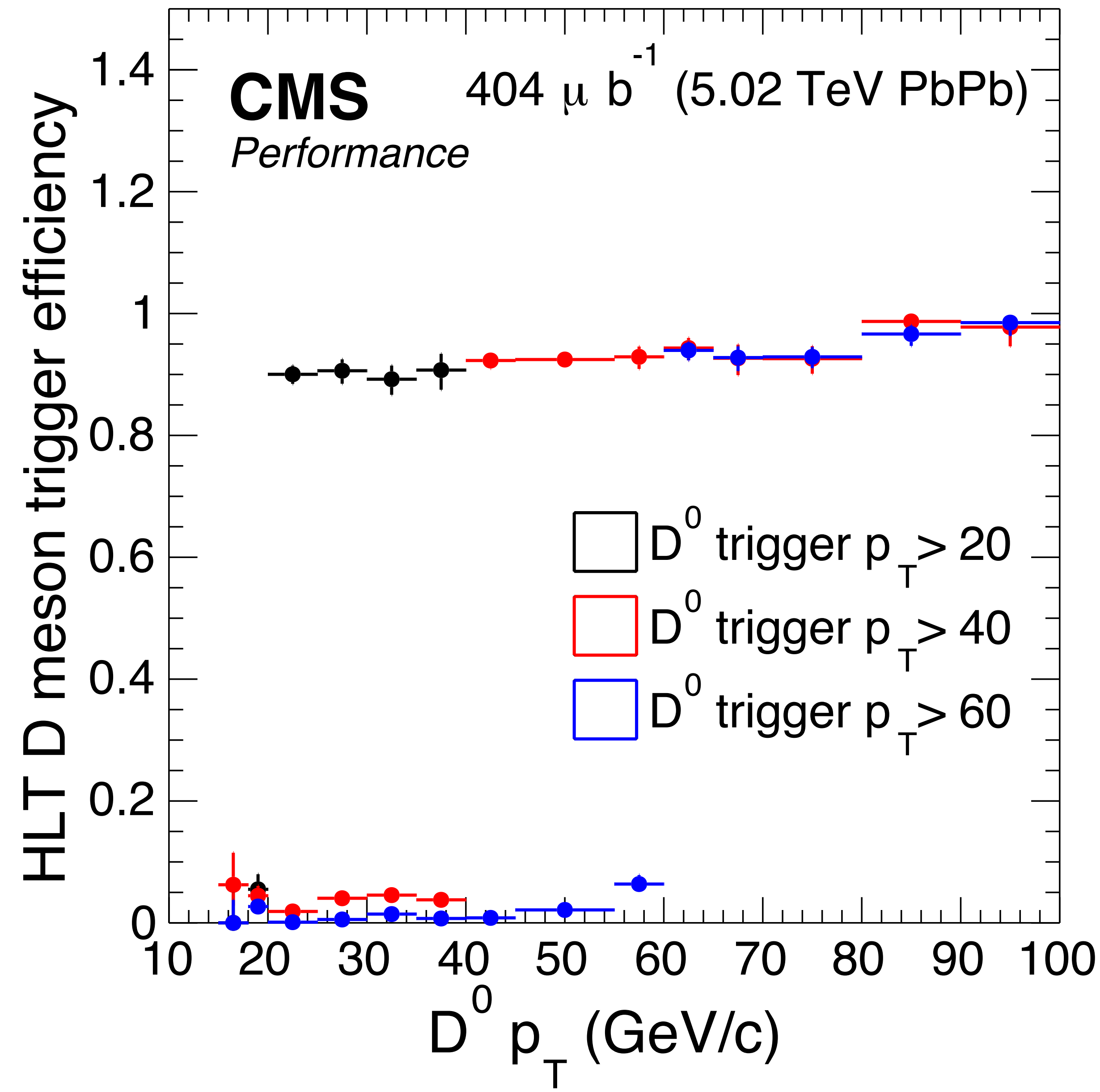
Track seed p_T cut applied:
- $p_T > 2$ GeV for pp
- $p_T > 8$ GeV for PbPb

D^0 meson are reconstructed

- Online D^0 reconstruction
- loose selection to reduce the rates based on D^0 vertex displacement

Performances of D^0 triggers





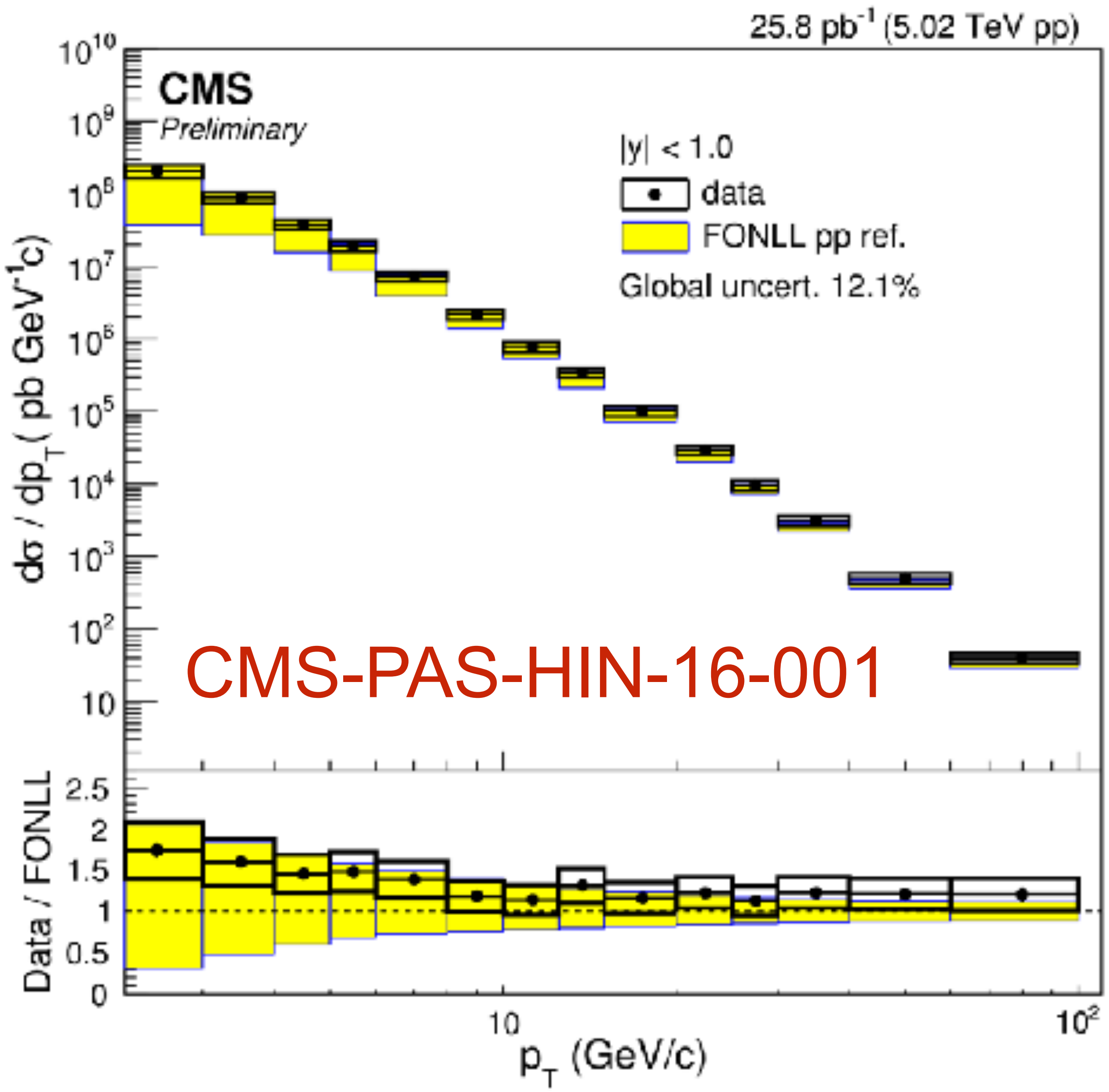
→ pp efficiency reaches 100% right above its D^0 p_T threshold

→ PbPb efficiency goes from ~90 to 100% depending on p_T

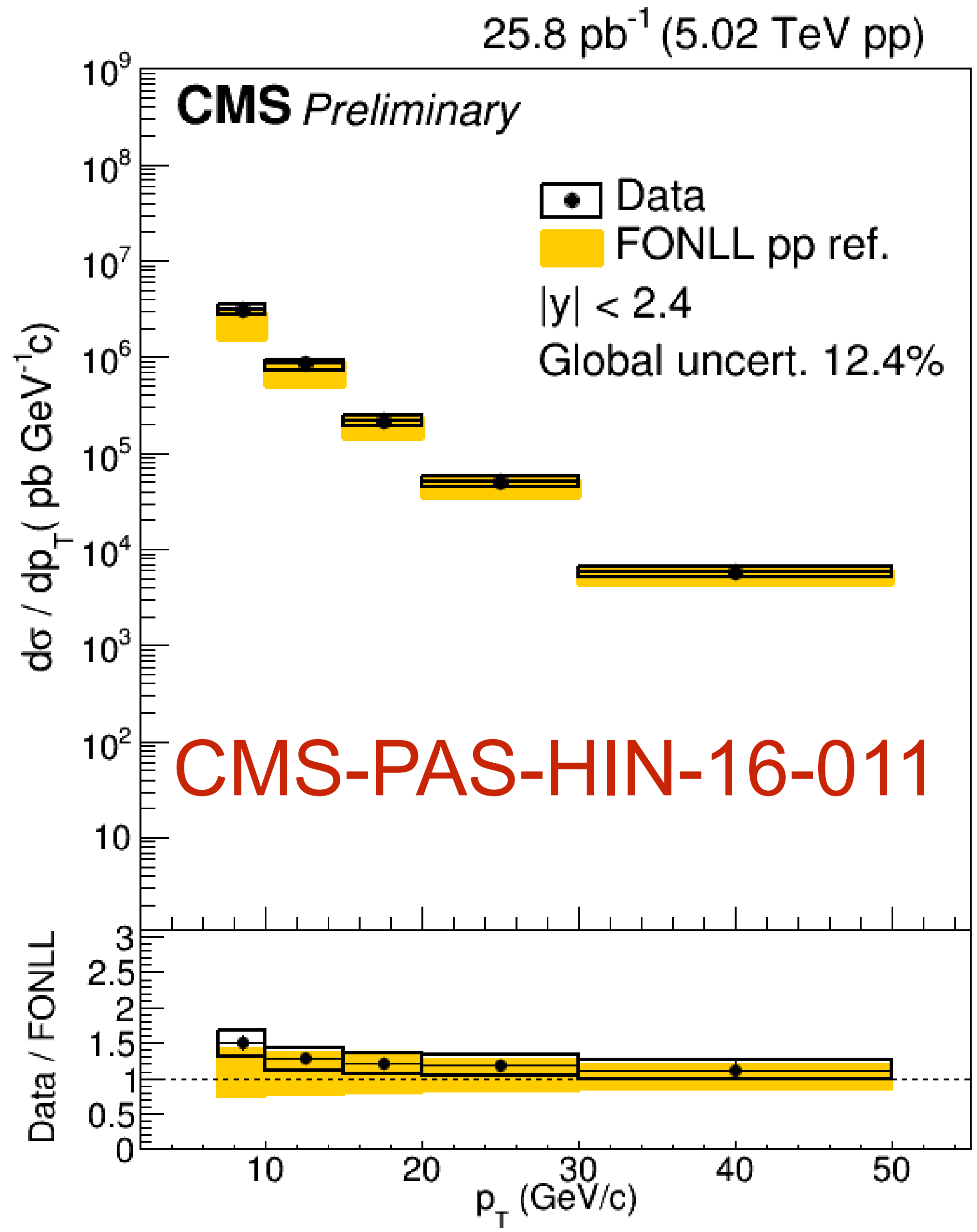
A quick summary of our results

D and B cross sections in pp collisions

D^0 at 5.02 TeV, |y|<1.0



B^+ measurement at 5.02 TeV, |y|<2.4



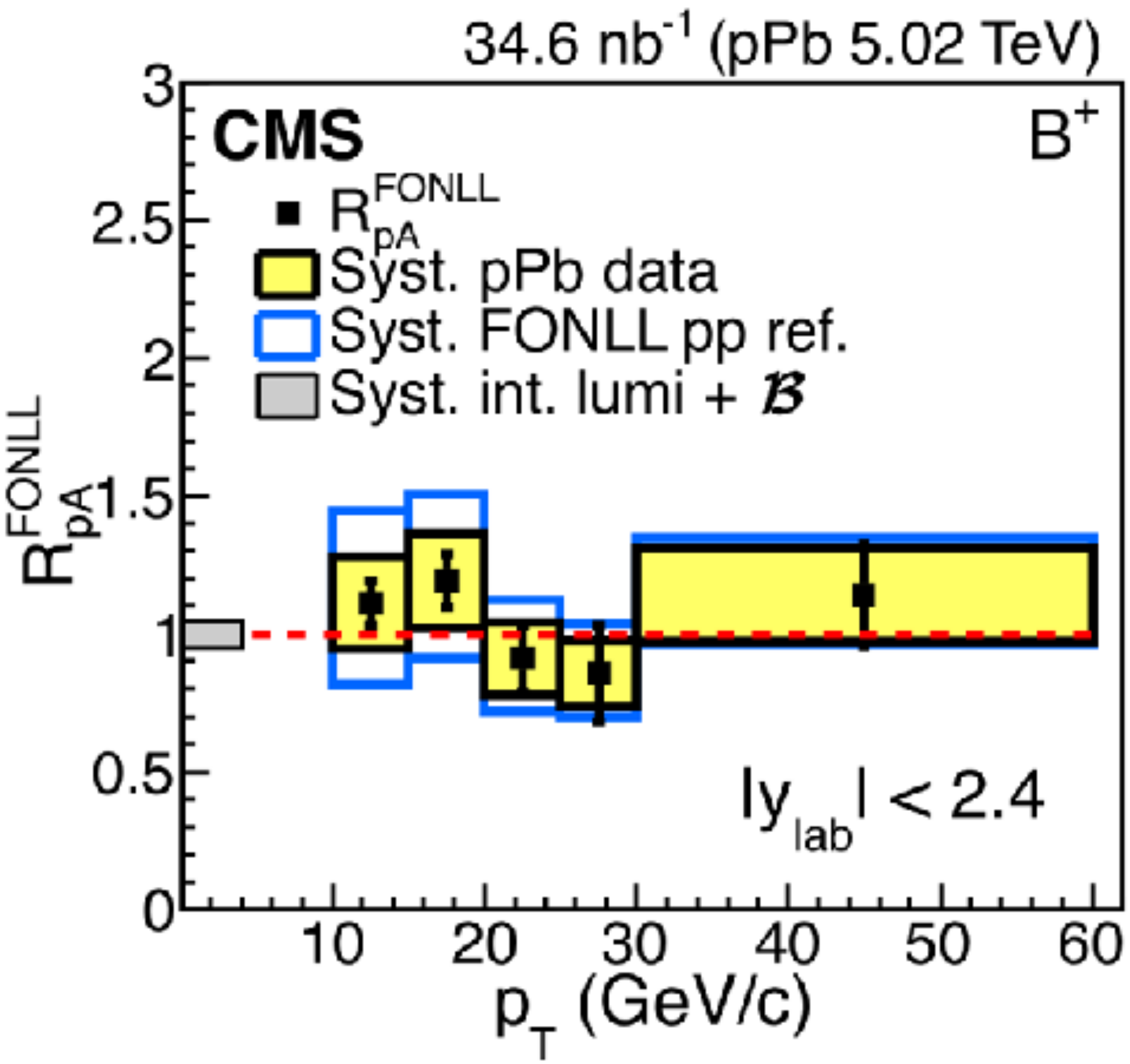
D and B meson production cross sections well described by NLO calculations:

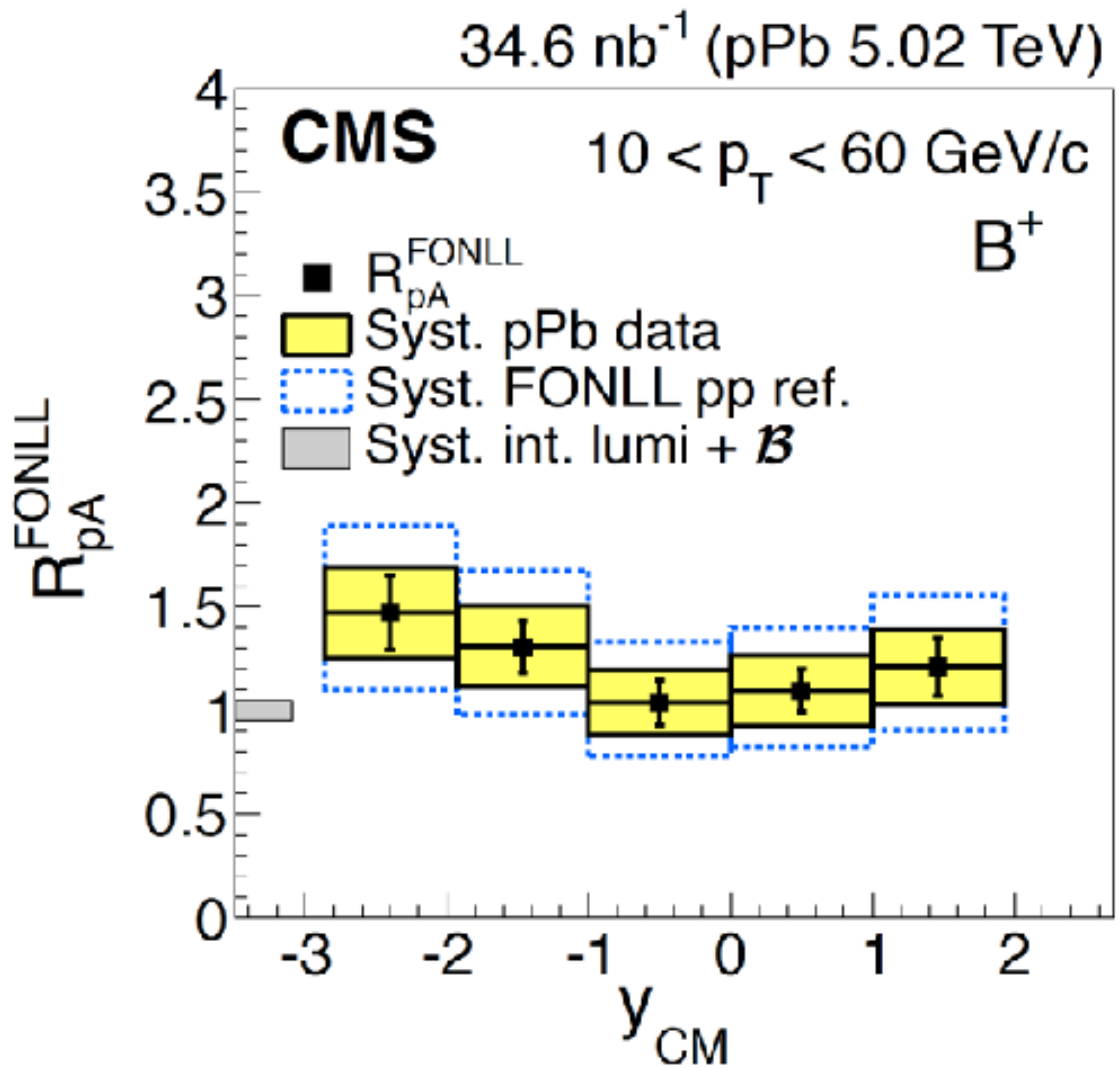
→*D meson upper edge of FONLL calculations*

→*B meson consistent with central values of FONLL at higher p_T,*
slightly higher for p_T<15 GeV

B meson production in pPb collisions

PRL 116 (2016) 032301





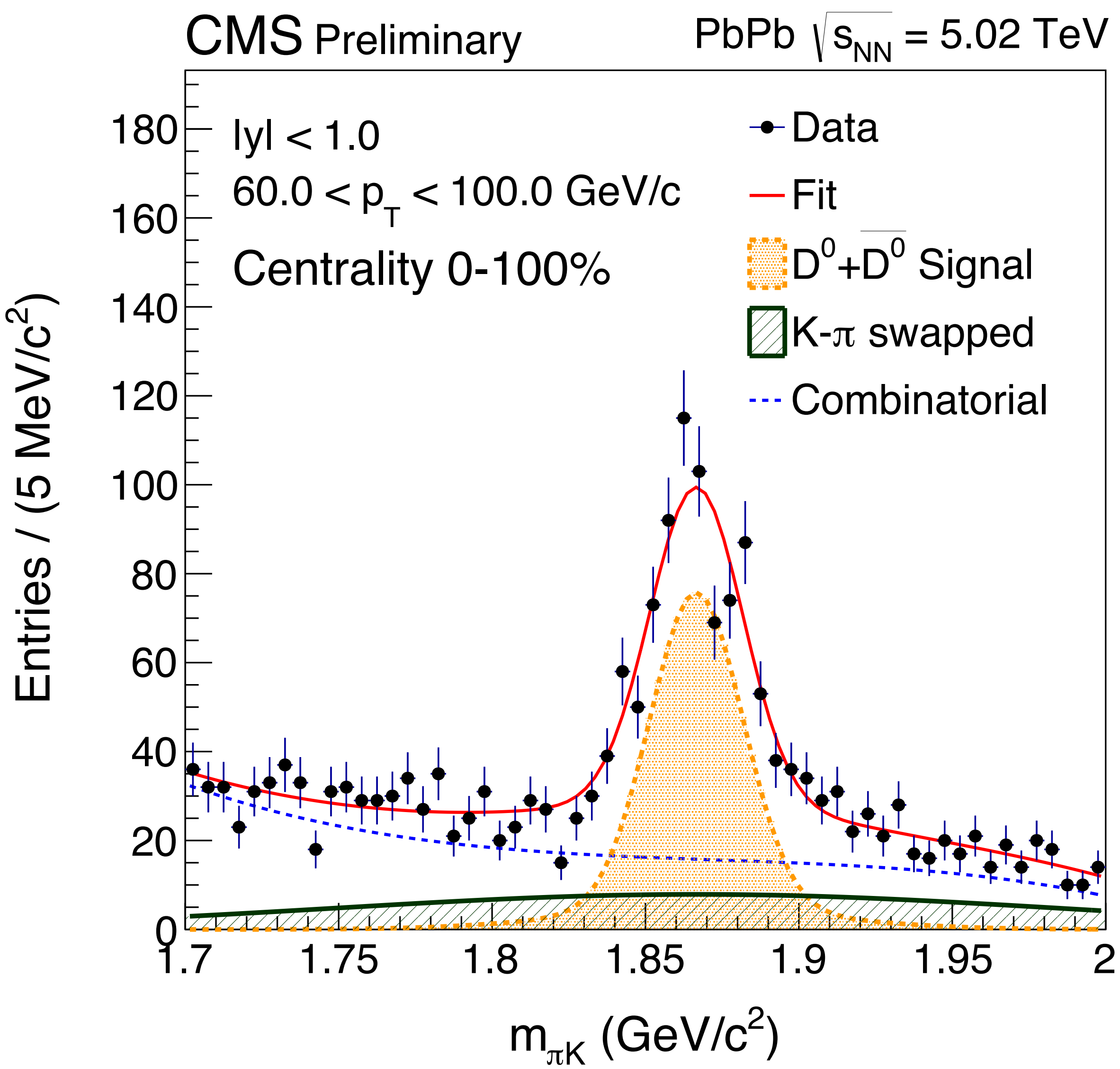
FONLL R_{pA} fully compatible with unity

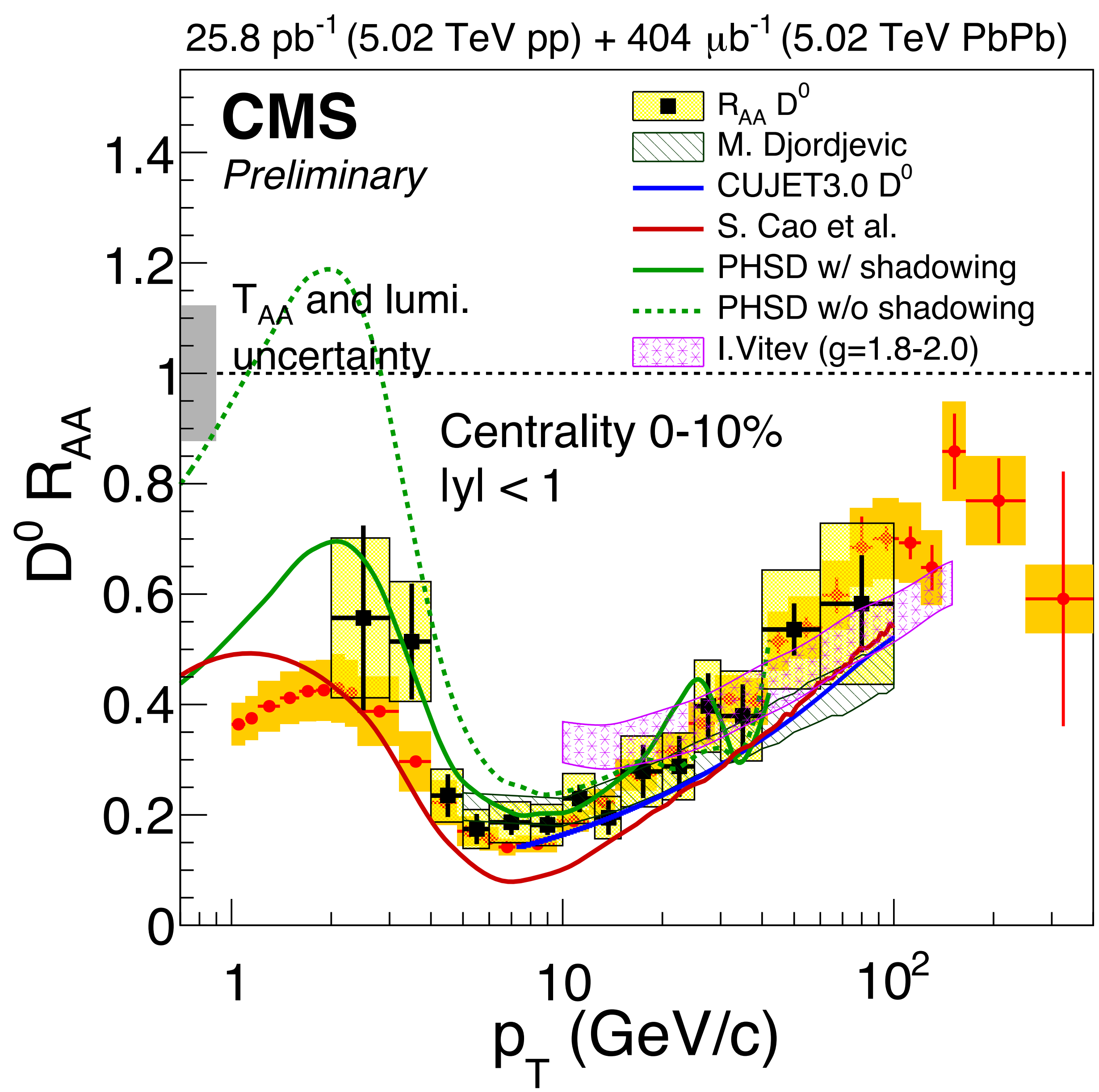
No sizeable modification as a function of rapidity

→ D R_{pA} and HF electron studies can give also complementary information!

D^0 meson R_{AA} at 5.02 TeV

D^0 R_{AA} measured from 2 to 100 GeV/c at central rapidity in 0-100%





→ ~300 MB events recorded for low p_T analysis

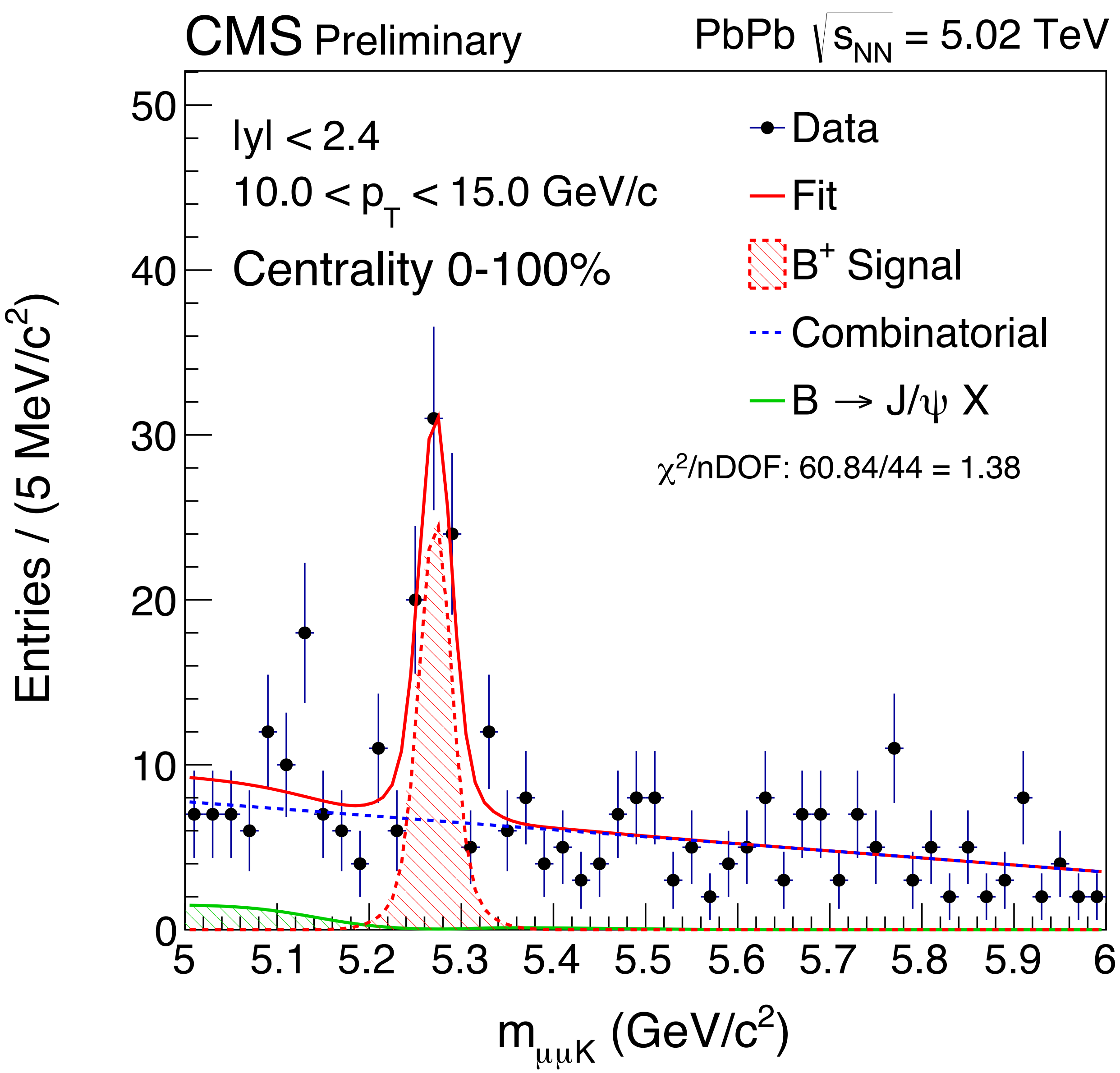
→ Dedicated triggers designed to perform full track reconstruction at HLT and to reconstruct and identify D^0 meson events at HLT

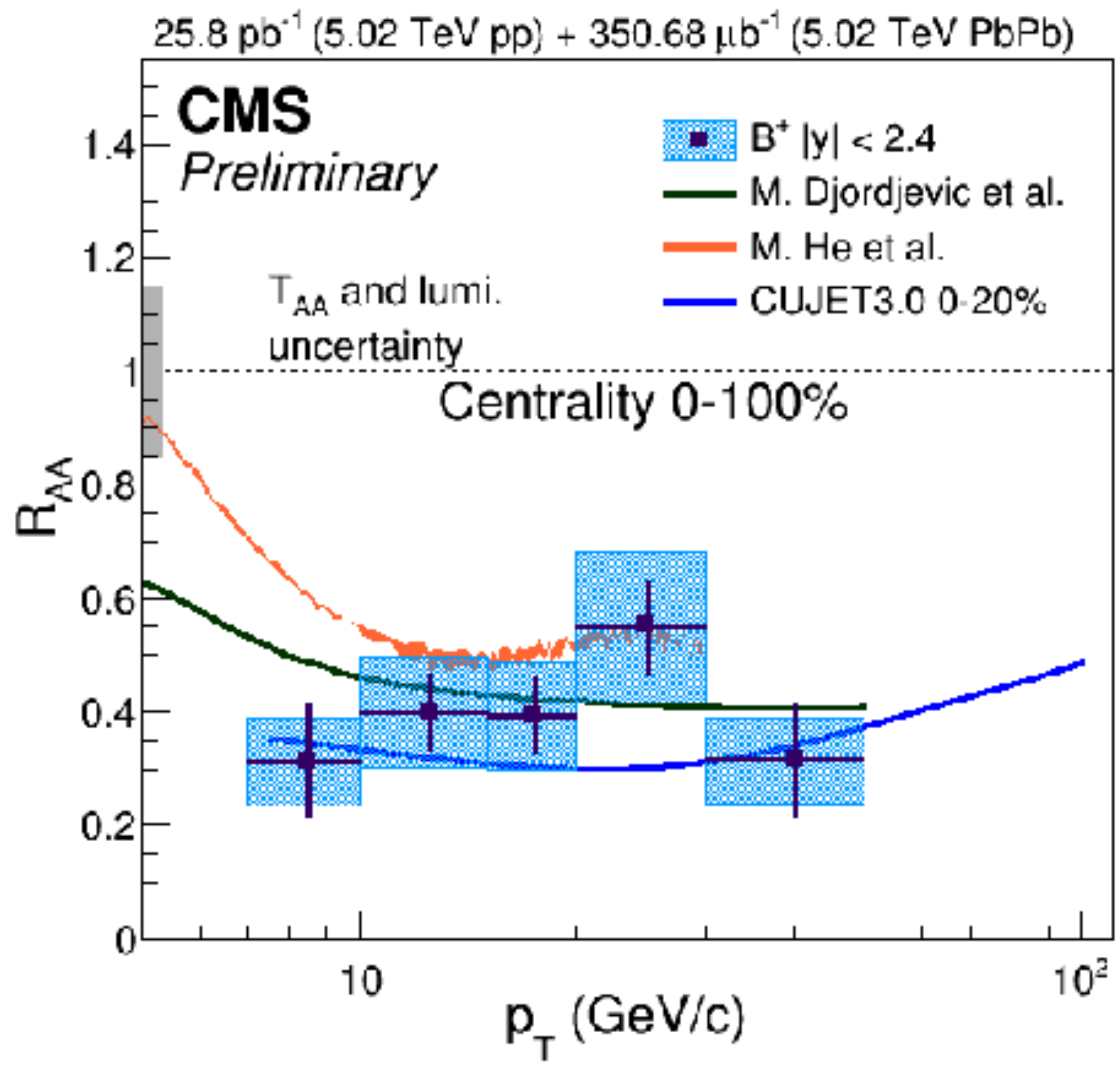
CMS-PAS-HIN-16-001

Exclusive B^{+} meson measurement in PbPb

CMS B^{+} production in PbPb at central rapidity |y|<2.4

CMS-PAS-HIN-16-011

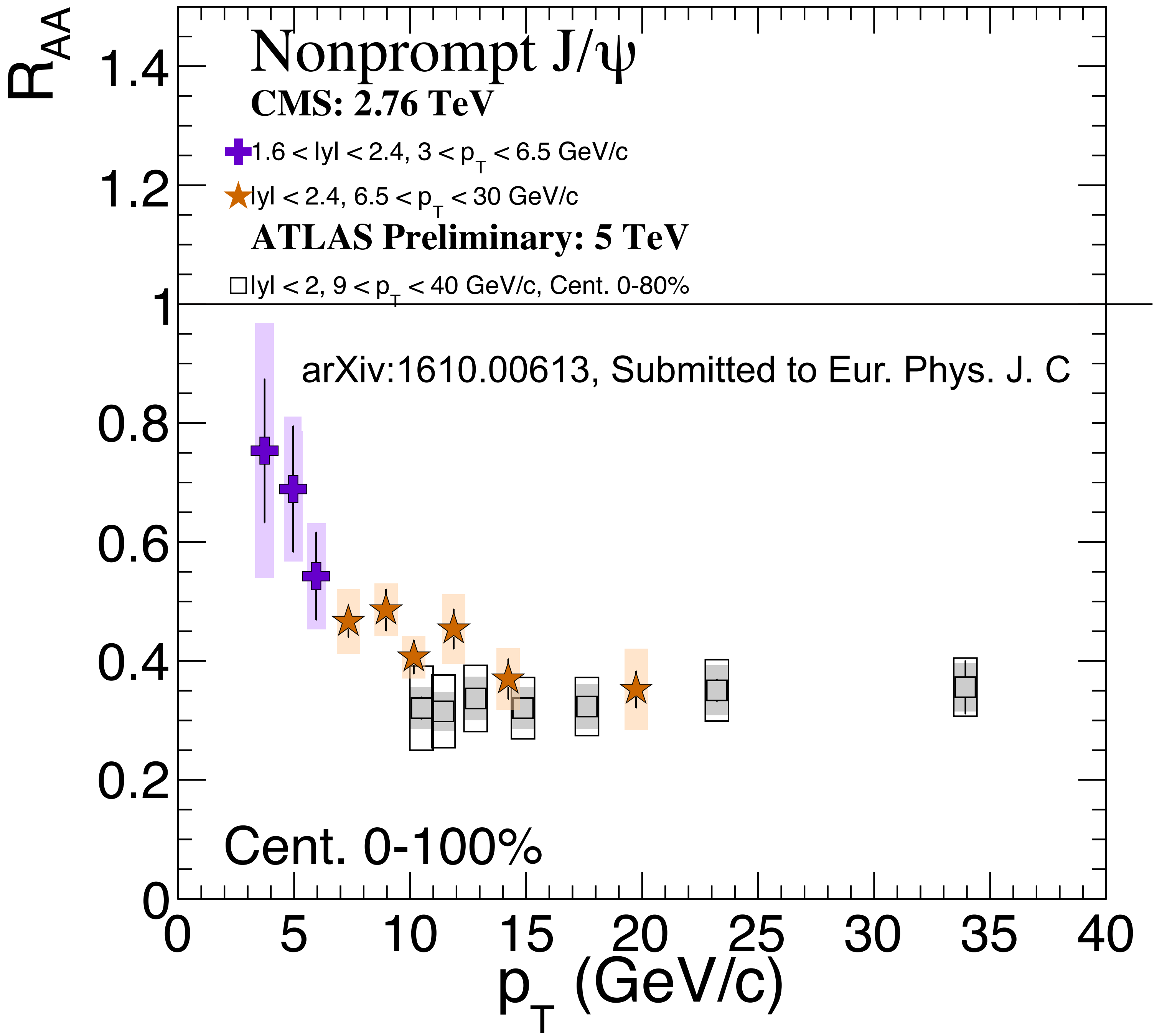




Strong suppression (R_{AA}~0.4) observed in 0-100% PbPb collision for p_T>7 GeV/c

Well described by theoretical calculations that include radiative energy loss

R_{AA} of non prompt J/ψ at 2.76 TeV



CMS non prompt 1.6<|y|<2.4

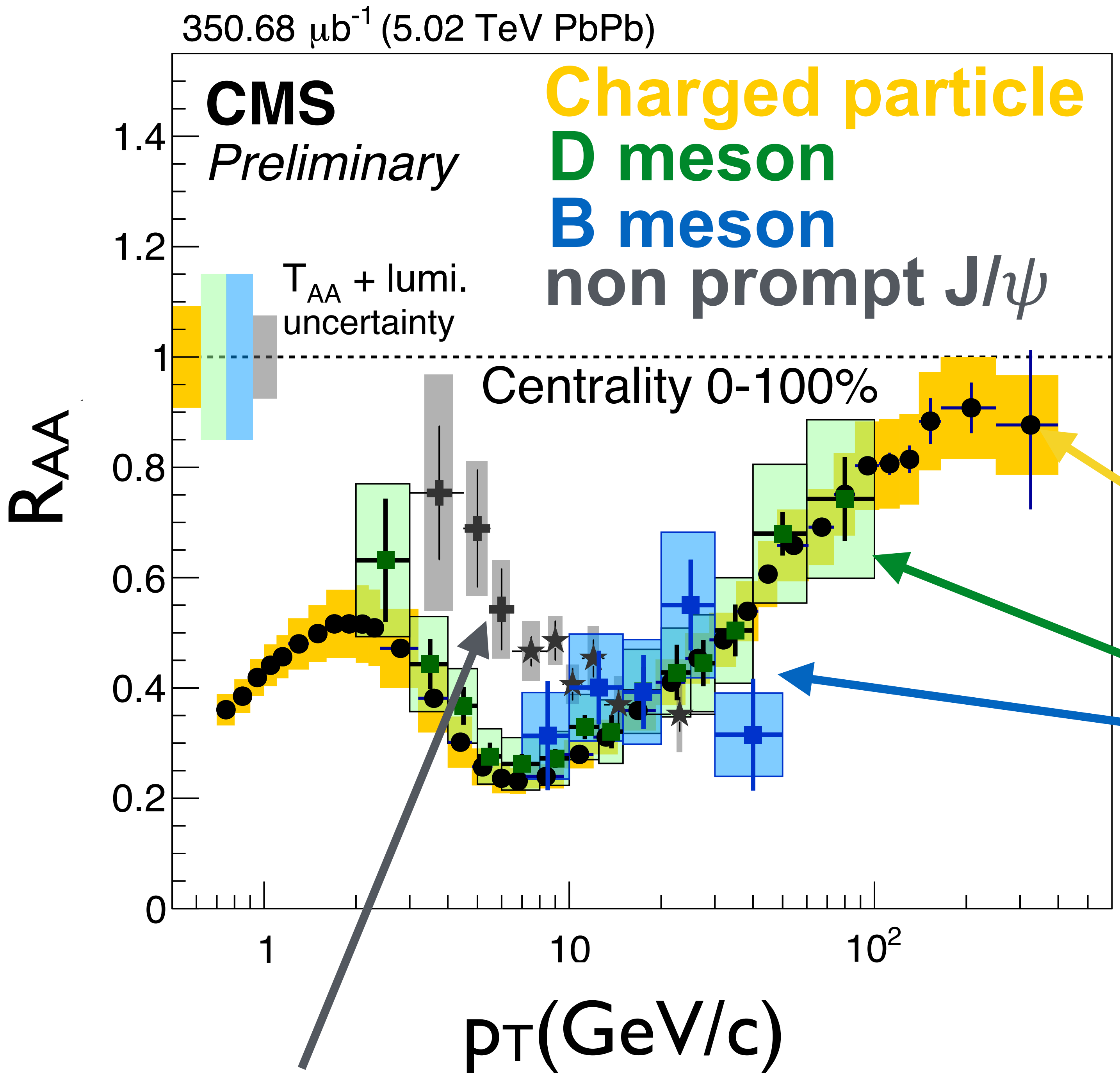
CMS non prompt |y|<2.4

ATLAS non prompt |y|<2.9

Strong suppression observed for non prompt J/ψ in PbPb collisions

→ **similar studies can be done in the c,b->electrons channel**

Flavour dependence at 5.02 TeV



Charged particle, D meson, B meson R_{AA} are consistent within uncertainties!

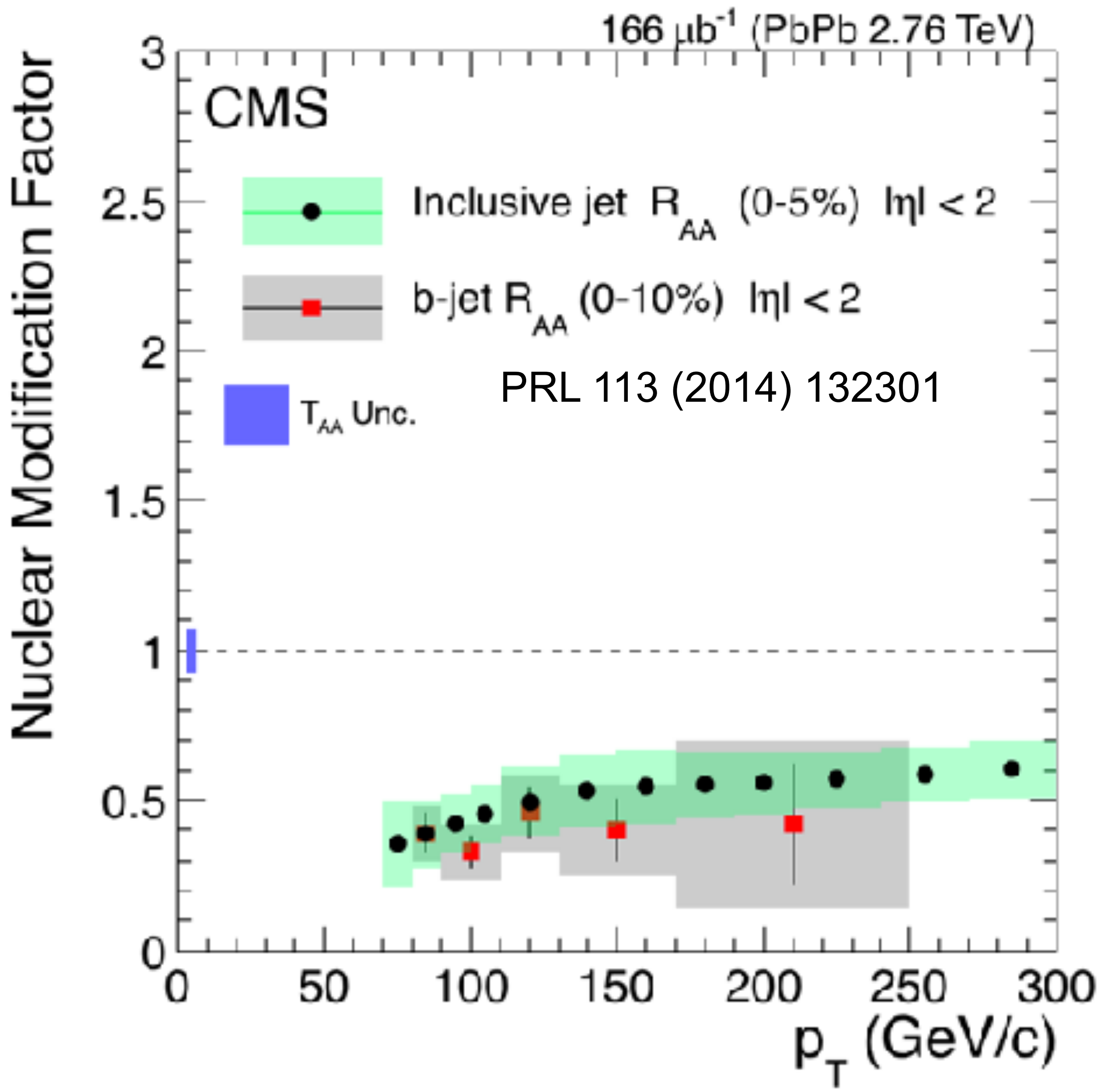
Charged particle

D meson

B meson

non prompt J/ψ at 2.76

Flavour dependence at higher p_T



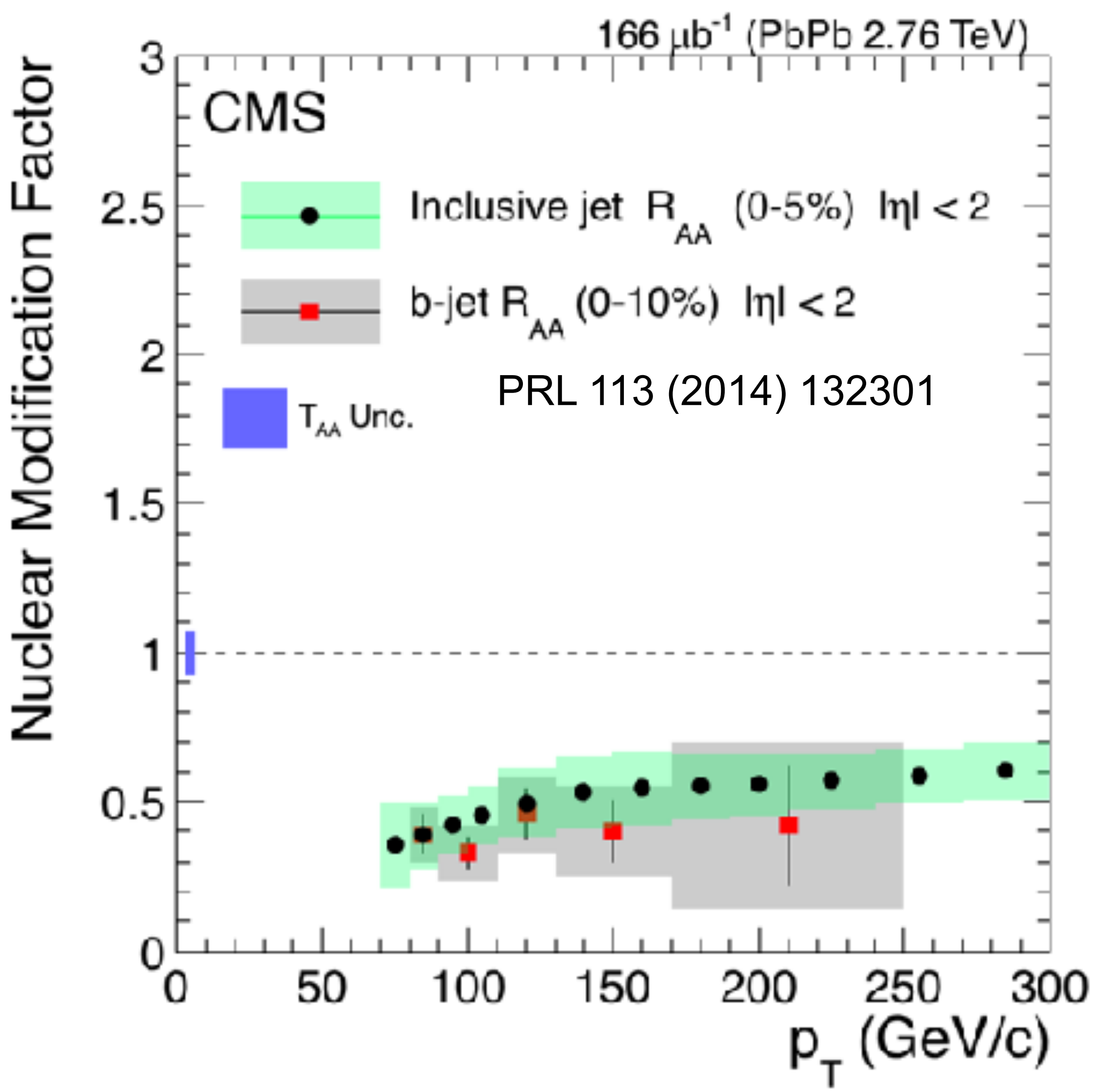
b-jet R_{AA}

inclusive jet R_{AA}

Same suppression for b-jets and inclusive jets at high p_T

Mass difference negligible at high p_T

Flavour dependence at higher p_T



b-jet R_{AA}

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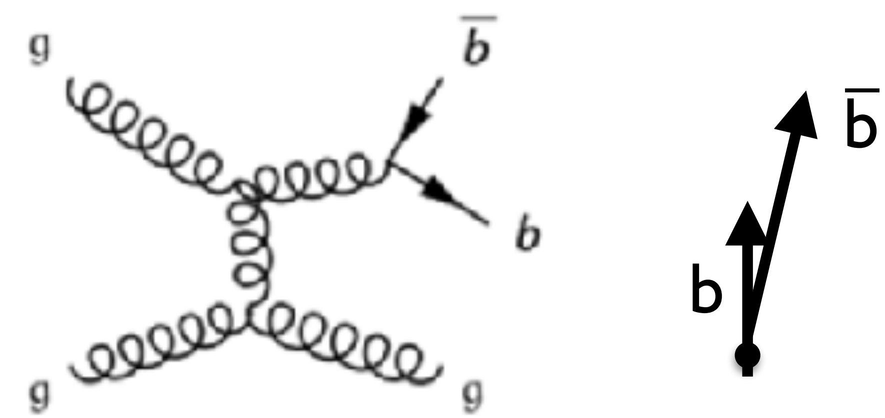


NLO process: Gluon splitting

→ dominant at low opening angles

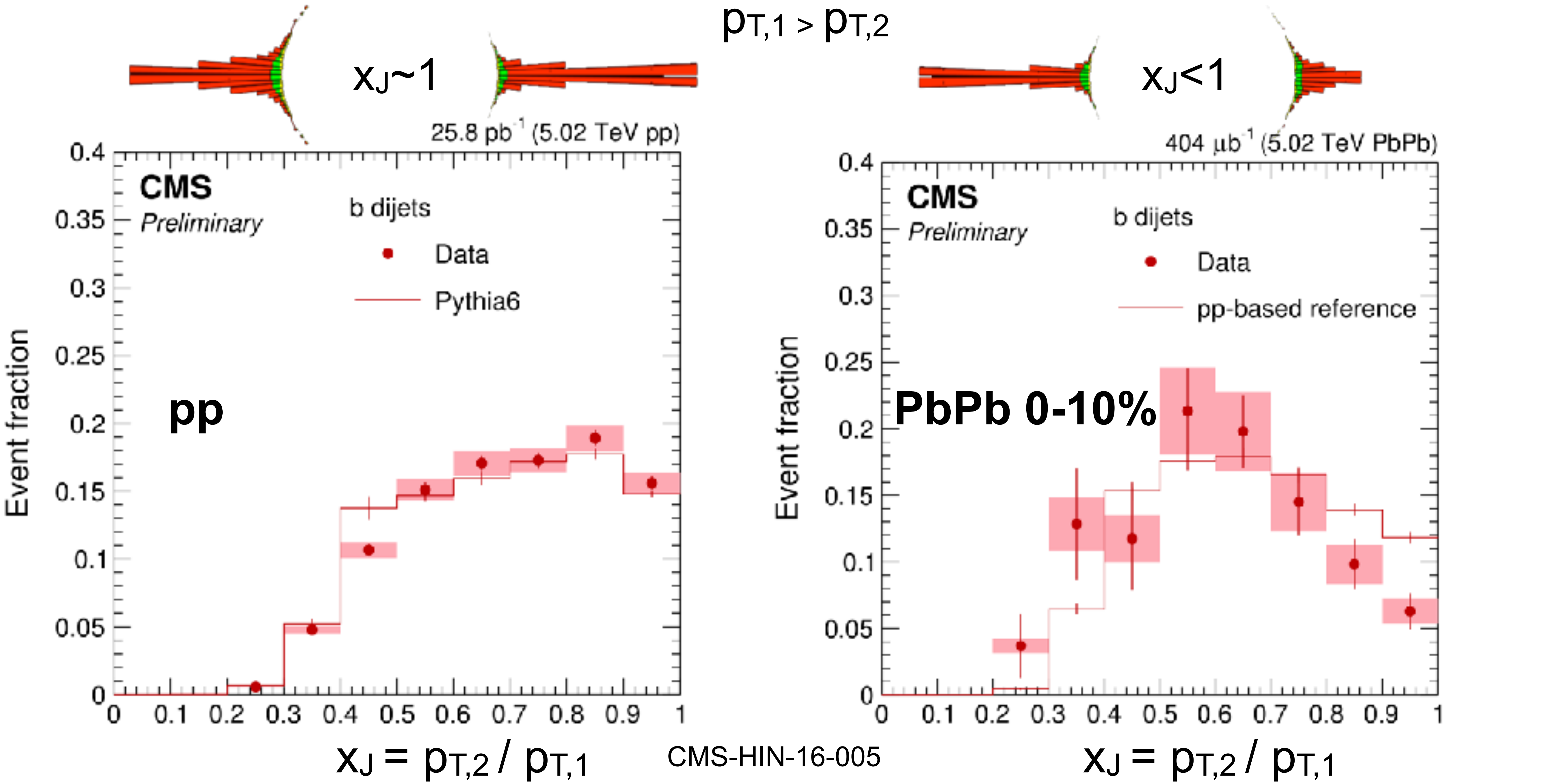
Same suppression for b-jets and inclusive jets at high p_T

Mass difference negligible at high p_T

***Large contribution of gluon splitting processes**? In GSP case, we are not measuring the b-quark E_{loss} but to some "fat" gluon E_{loss}*

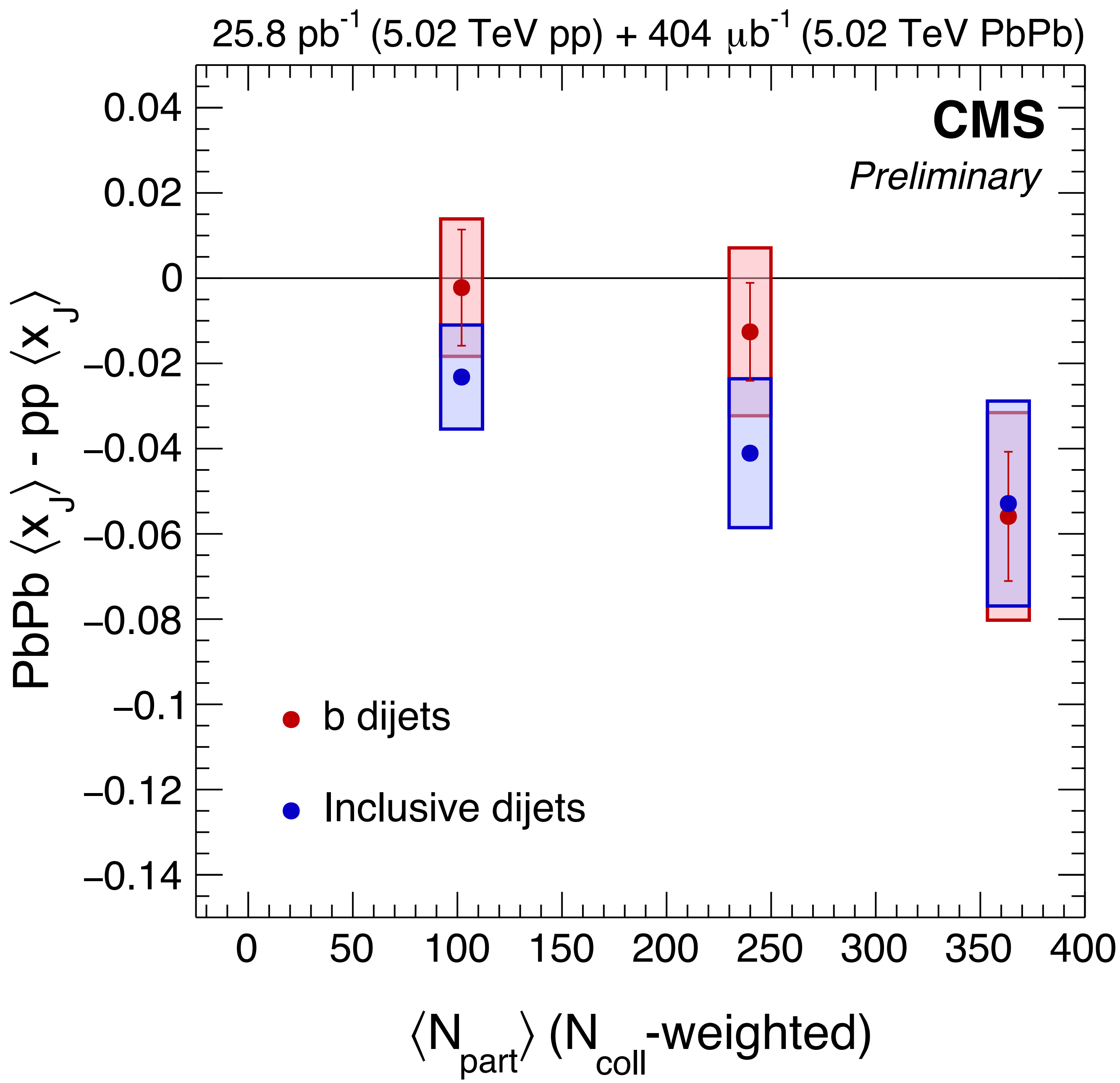
Di-b-jet measurement in PbPb at 5.02 TeV

→ In back-to-back events $b\bar{b}$ production via gluon splitting processes is negligible



x_J distributions of di-b-jets significantly modified in central PbPb collisions!

Di-b-jet measurement in PbPb at 5.02 TeV



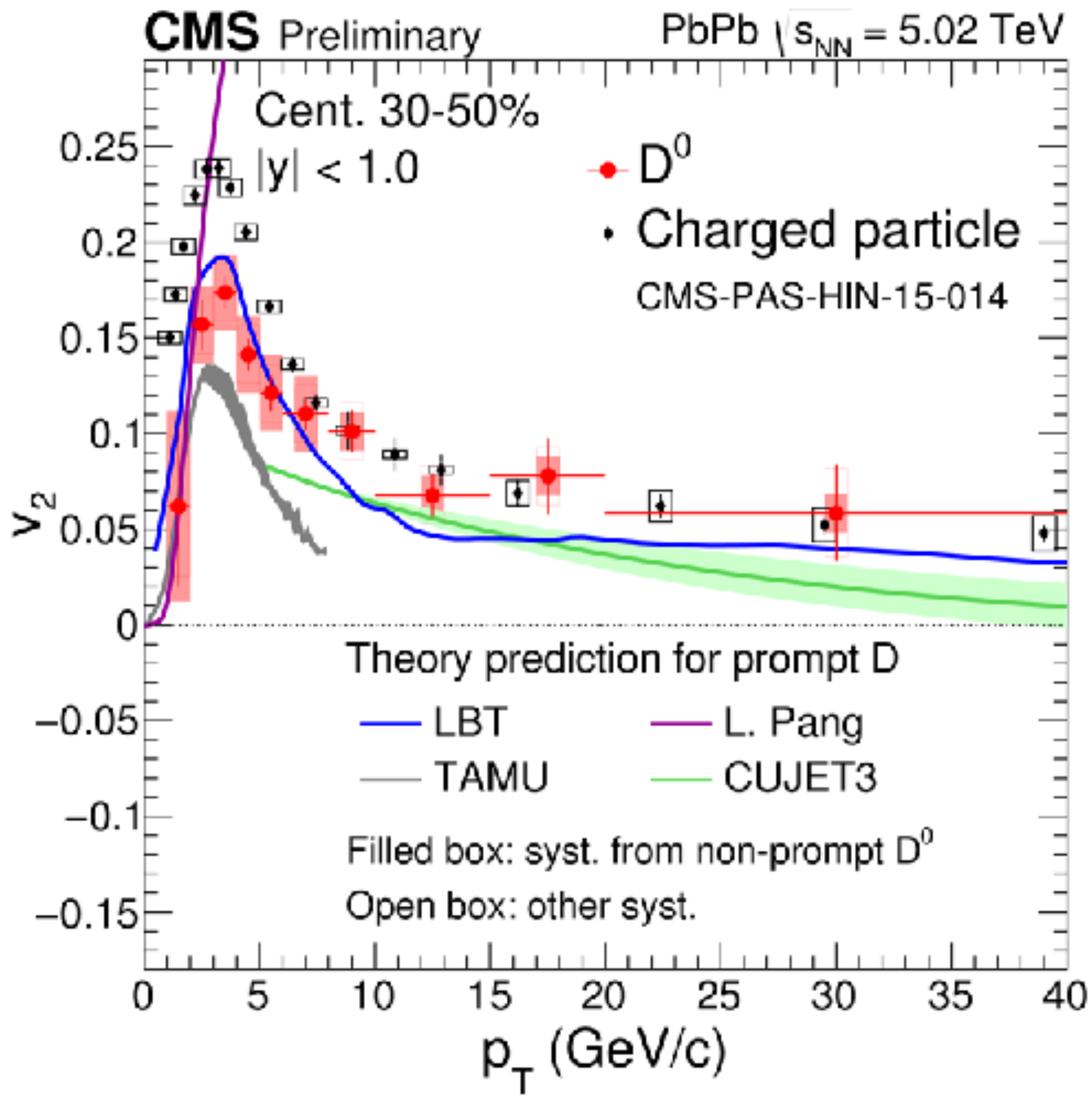
$x_J = p_{T,2} / p_{T,1}$

Same average asymmetry observed for inclusive jets!

CMS-HIN-16-005

There is no significant difference in the suppression of inclusive and b-jets even after excluding the contribution of gluon splitting processes

D^0 elliptic flow in PbPb collisions



CMS-PAS-HIN-16-007

we need **charm quark diffusion** to describe the magnitude of the D meson v_2

Summary and conclusions

CMS experiment showed to be an excellent detector for HF measurements thanks to:

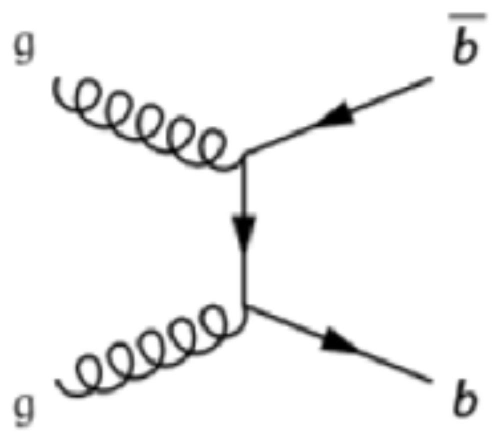
- excellent tracking and vertexing system
- efficiency di-muon trigger system and capability to trigger on HF probes
- possibility to run at very high luminosity and collect huge amount of MB
- PID (that is still in possible in CMS with pixel) is important but not fundamental

How can sPHENIX be complementary:

- both low pT (flow, collectivity) and high pT (jet queching, flavour dependence) are still not completely understood.
- sPhenix could collect huge amount of data to help solving both the puzzles
- the possibility of having both data at LHC and RHIC energies is a unique opportunity to validate theoretical calculations that are now very well “tuned” at LHC.

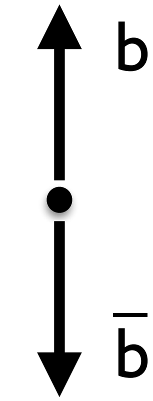
BACKUP

heavy quark production mechanism



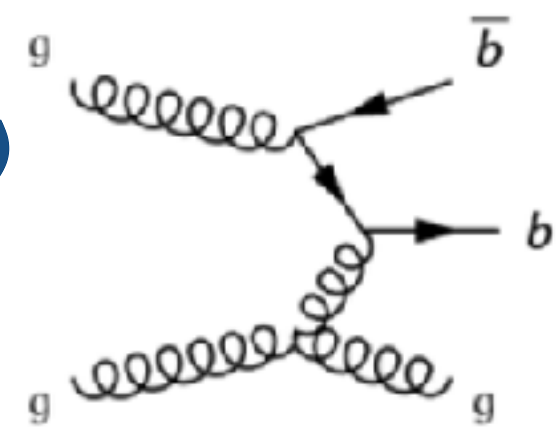
LO process: Flavour Creation (FCR)

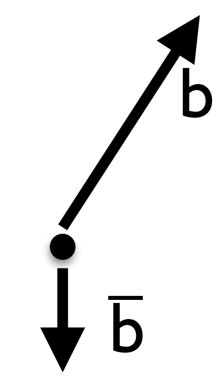
→ $b\bar{b}$ produced back-to-back in azimuthal plane and symmetric in p_T

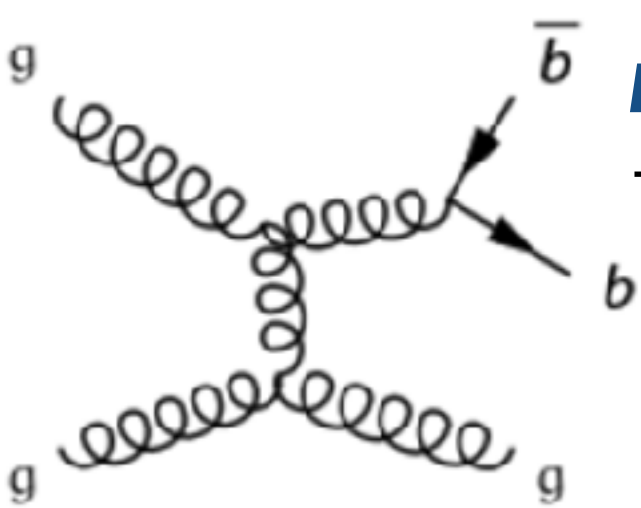


NLO process: Flavour Excitation (FEX)

→ $b\bar{b}$ pairs produced asymmetric in p_T and with a broad opening angle



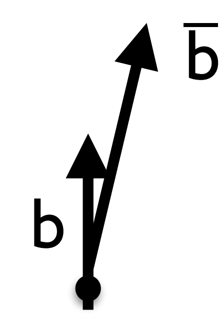




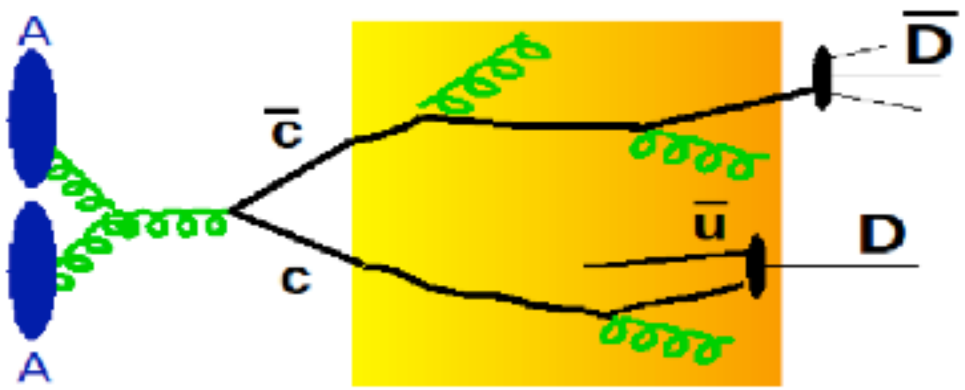
NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T

→ $b\bar{b}$ are not involved in the hard scattering but produced later

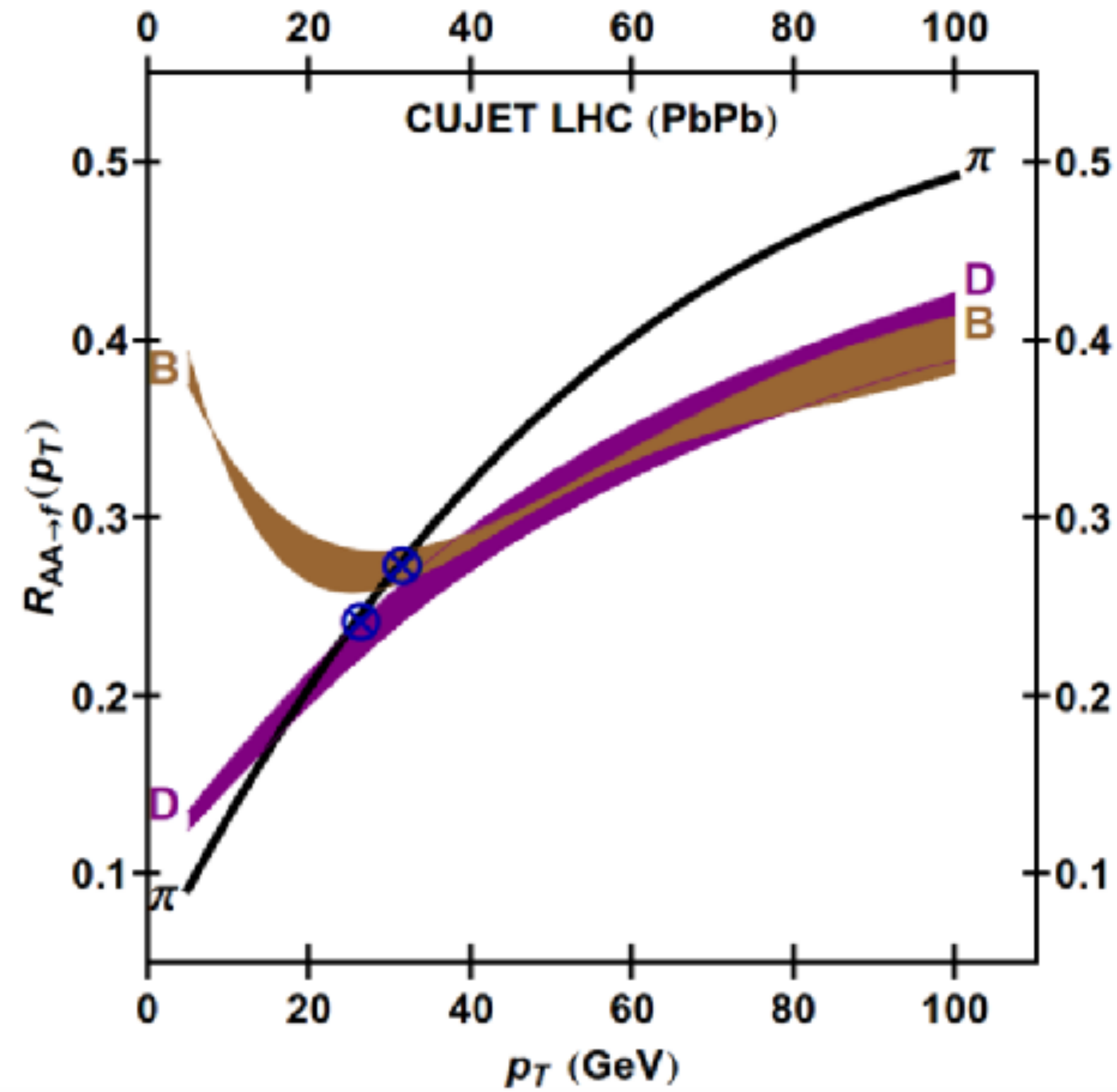


Reminder on HF energy loss



- produced early in the collision, they strongly interact with the deconfined medium

→ In-medium energy loss as a consequence of radiative and collisional processes.



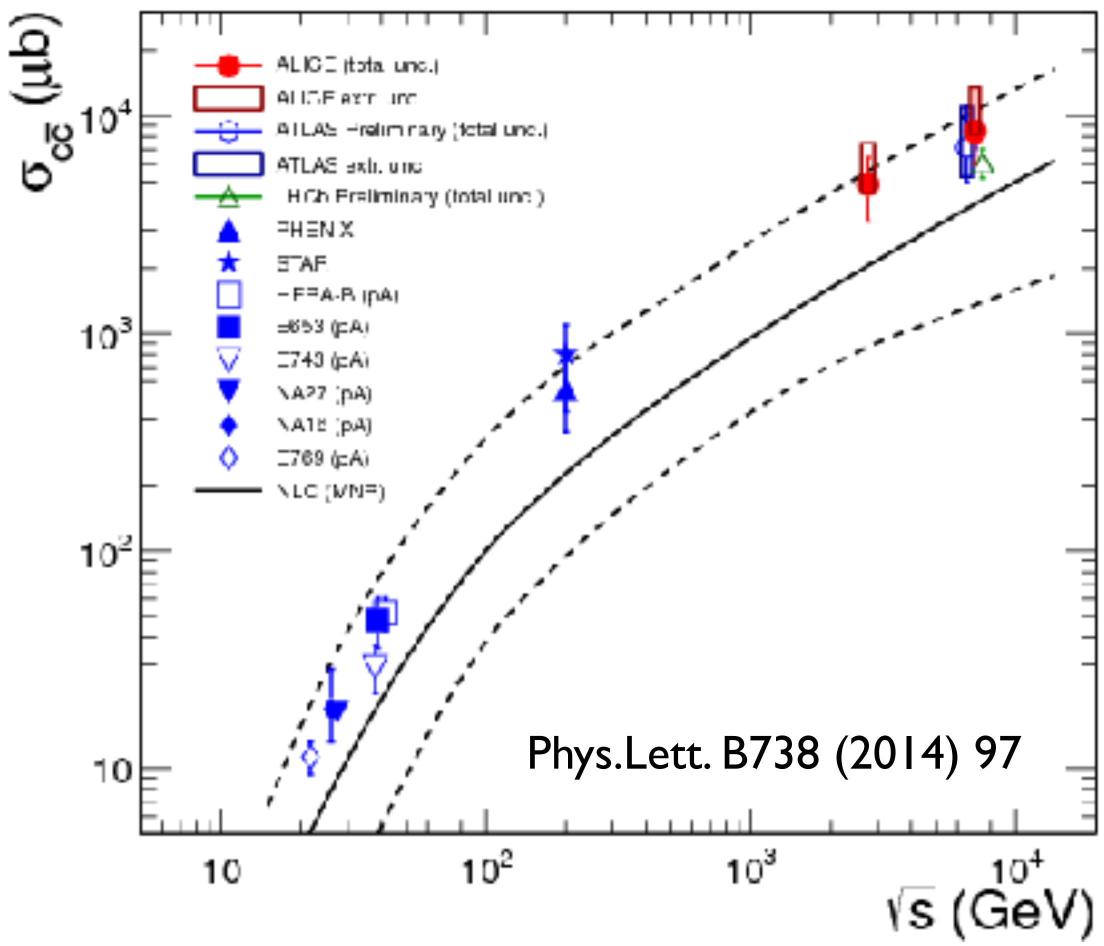
Flavour-dependence of radiative energy loss:

- Larger for gluons than for quarks
  E.g. in BDMPS model [1] $\langle\Delta E\rangle \propto \alpha_s C_R q L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ → $R_{AA}^B > R_{AA}^D > R_{AA}^{light}$ (??)

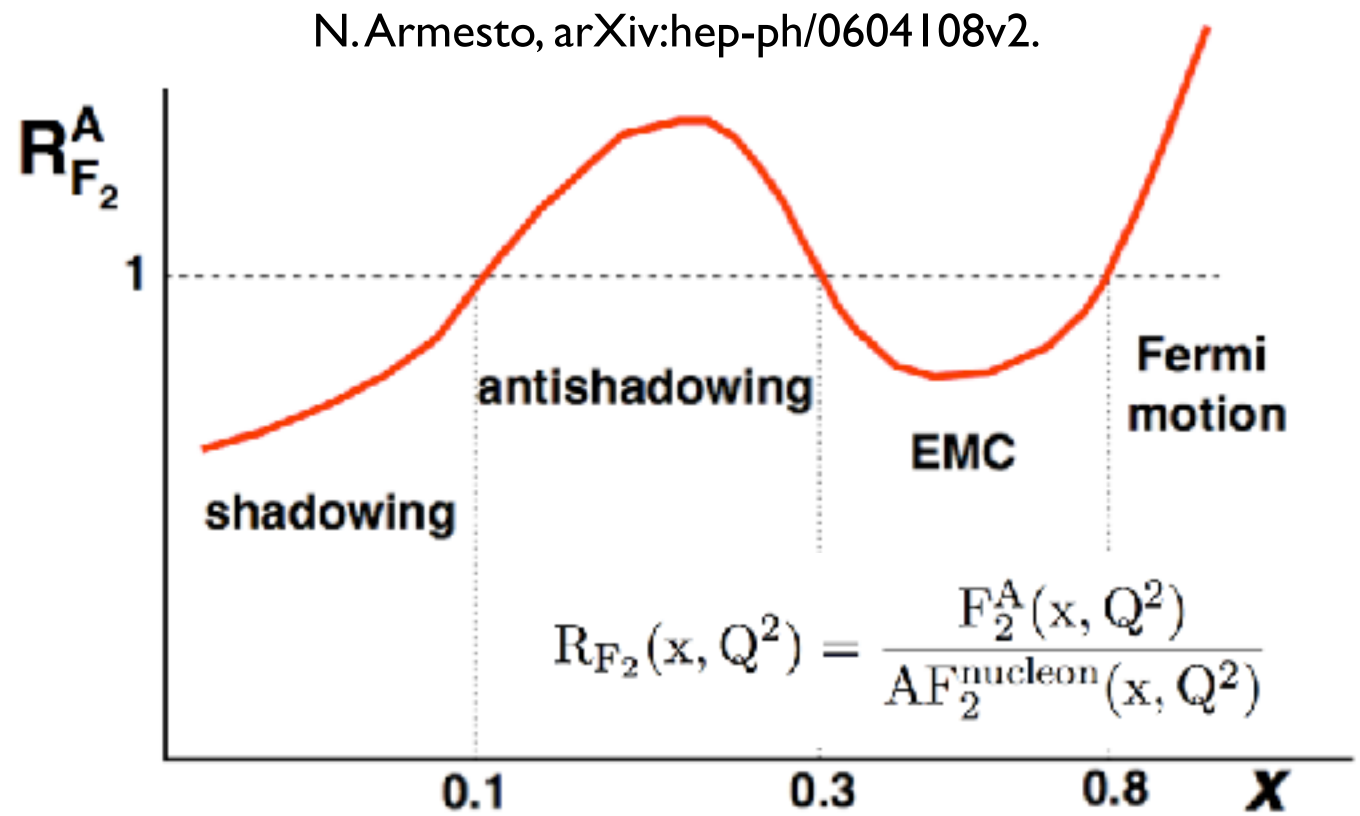
Heavy-flavours in pp and pPb collisions

Heavy quarks produced in high Q^2 processes at early stages of the collisions



pp:
- test of pQCD calculations
- reference for pA and AA measurements

N. Armesto, arXiv:hep-ph/0604108v2.

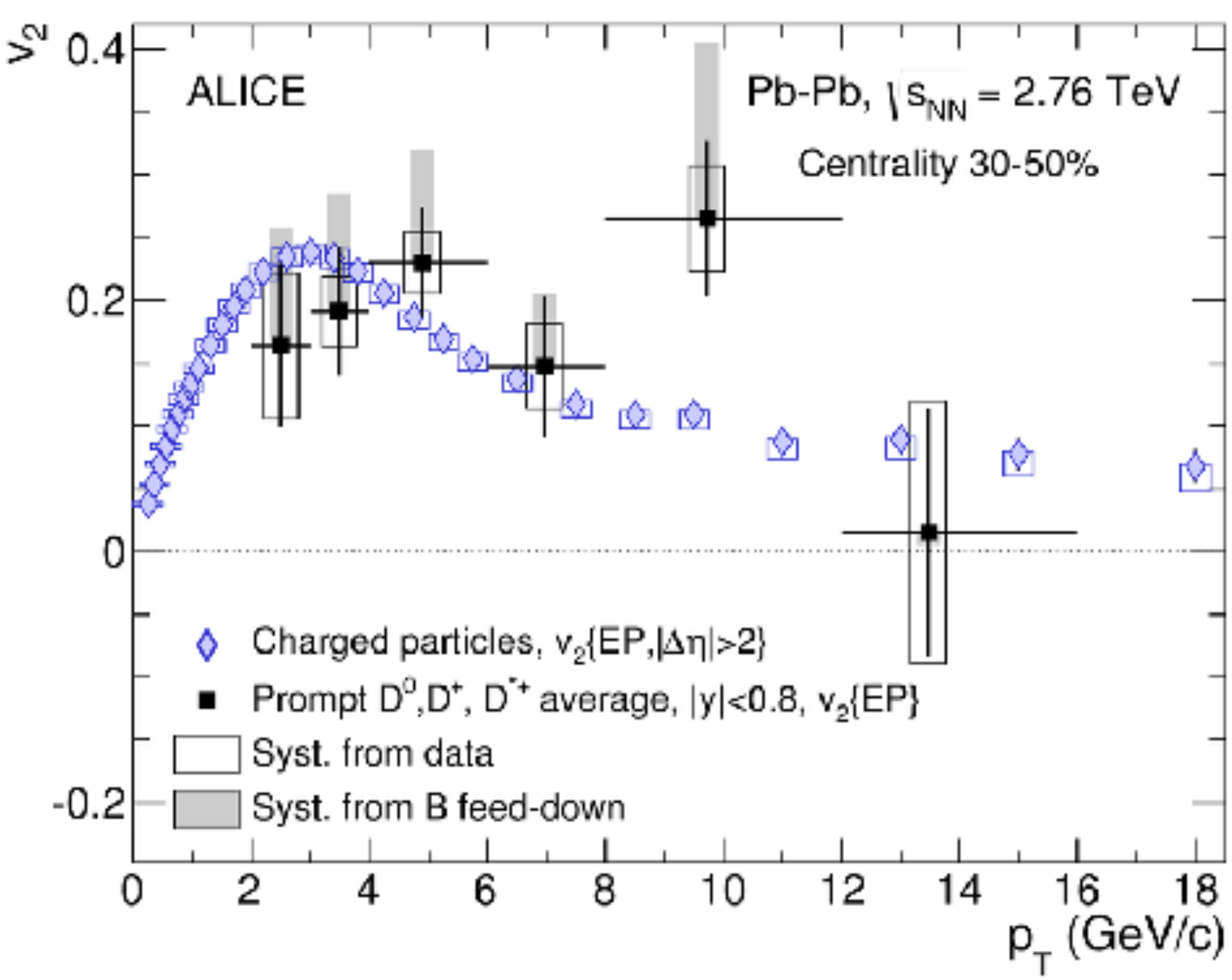


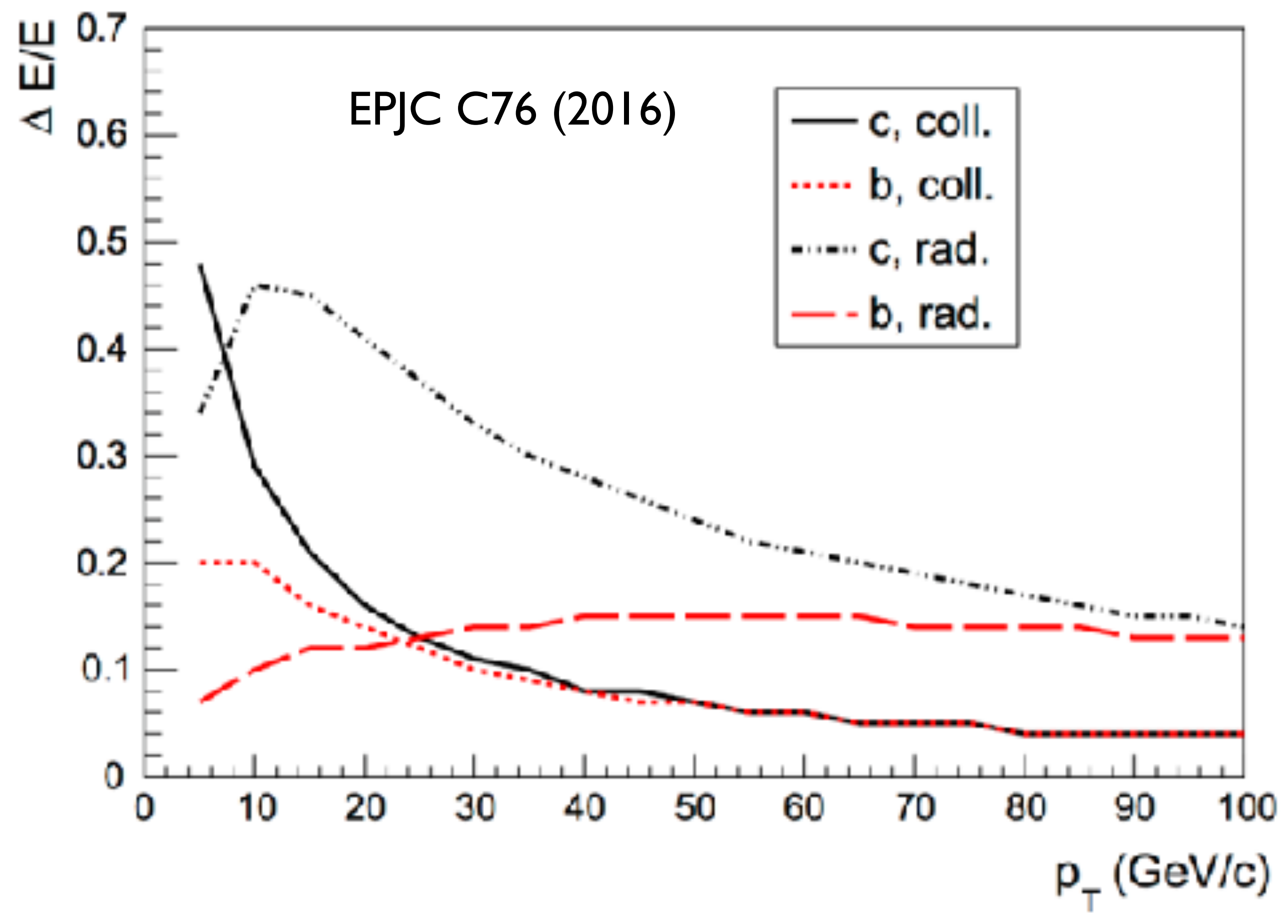
pPb:
- test of cold nuclear matter effects
  - PDF modifications
  - saturation
  - final state effects
- collective evolution (hydro?)

Heavy-flavours in PbPb collisions

Heavy quark energy loss in PbPb:
- **collisional** vs **radiative** component

Flavour dependence energy loss:
- $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$
- Dead cone effect: gluon radiation suppressed at small angles for massive quarks





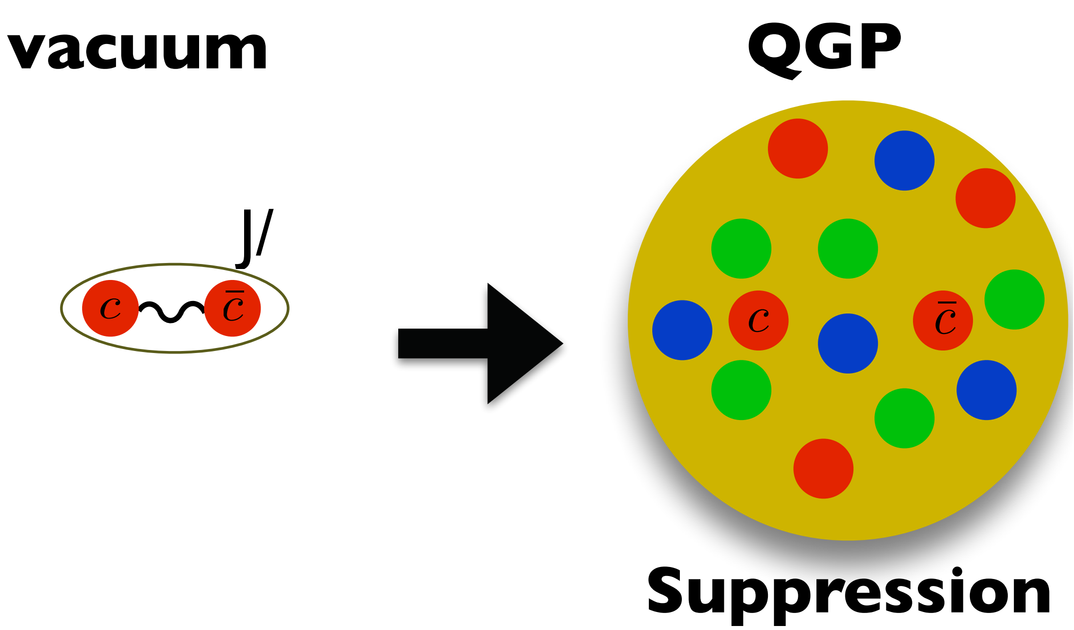
Collective behaviour:
- v_n measurements to study collective behaviour of heavy quarks
- charm recombination in medium?

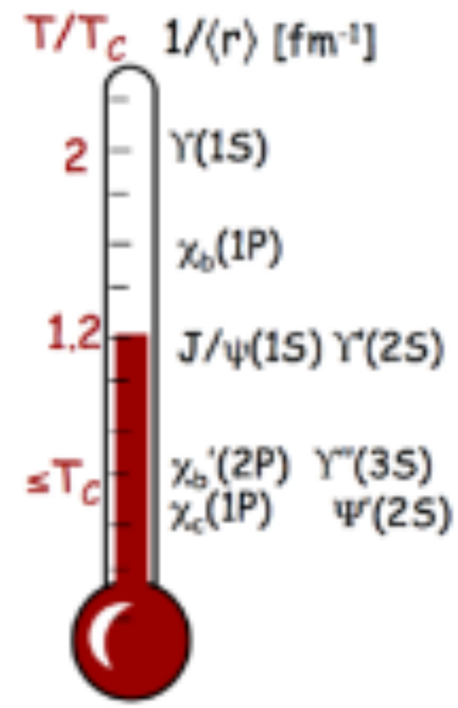
Charmonia in heavy-ion collisions

Charmonia are bound states of $c\bar{c}$

$$\tau^{c\bar{c}}_{\text{formation}} \lesssim \tau^{QGP}_{\text{formation}} < \tau^{QGP}_{\text{life}} < \tau^{\text{quarkonium}}_{\text{decay}}$$

The presence of QGP should affect charmonia production (yield and kinematics)





Less bounded states melts at lower temperature
T$^{\text{diss}}$ (1S) > T$^{\text{diss}}$ (2S) > …

We should observe a hierarchy in the dissociation of different quarkonia states depending on their binding energies

Charmonia in heavy-ion collisions

Charmonia are bound states of $\bar{c}c$

$$\tau^{c\bar{c}}_{\text{formation}} \lesssim \tau^{QGP}_{\text{formation}} < \tau^{QGP}_{\text{life}} < \tau^{\text{quarkonium}}_{\text{decay}}$$

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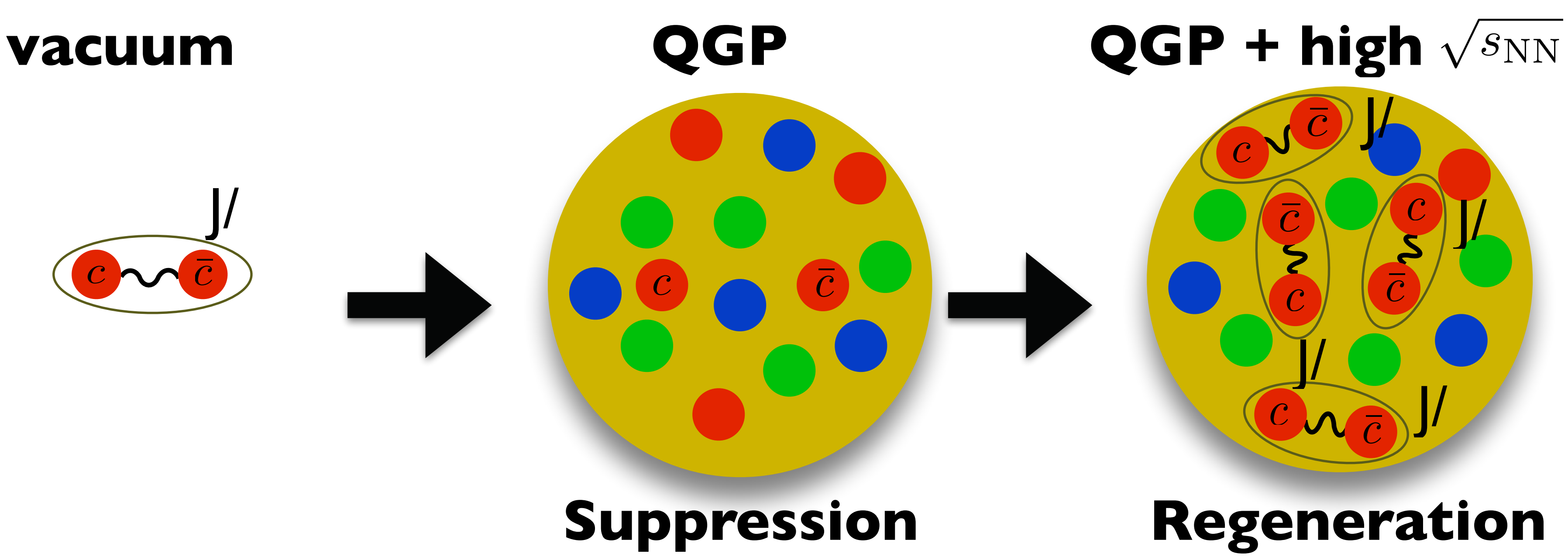
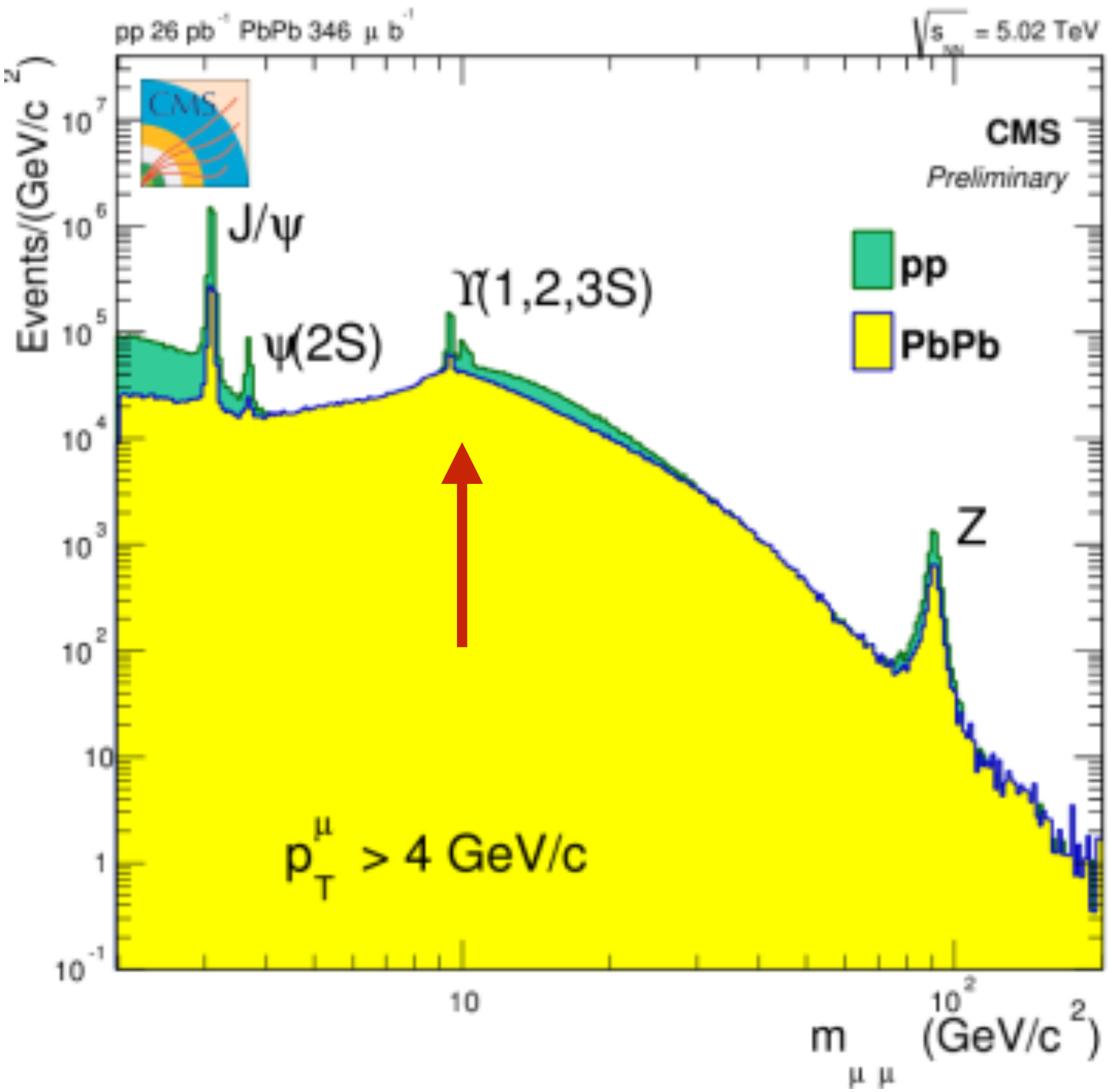


Less bounded states melts at lower temperature

T^{diss} (1S) > T^{diss} (2S) > …

But life is not that easy, charm (re)combination in the medium is expected to play a significant role at LHC!

Bottomonia, a cleaner probe for the QGP



Y(nS) states are less likely to be created via recombination!

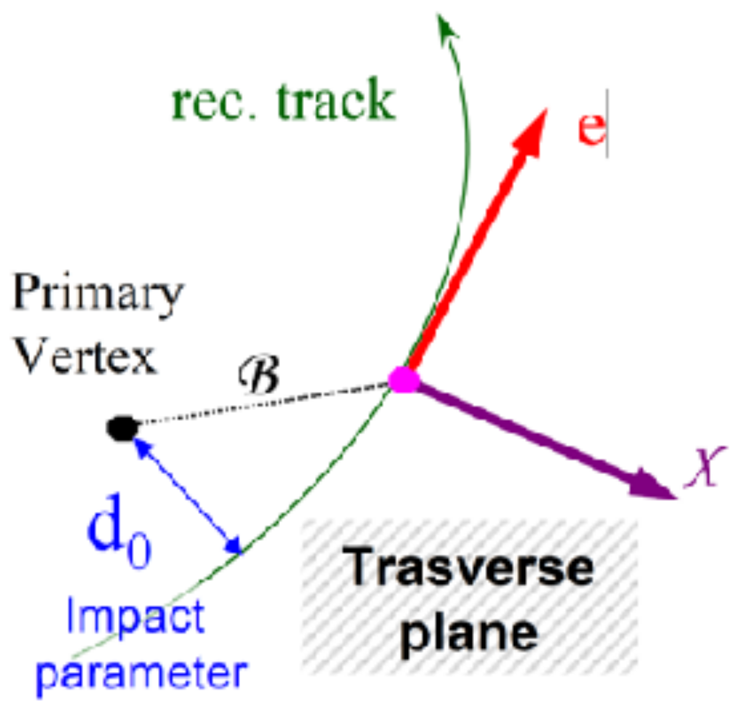
HF models overview

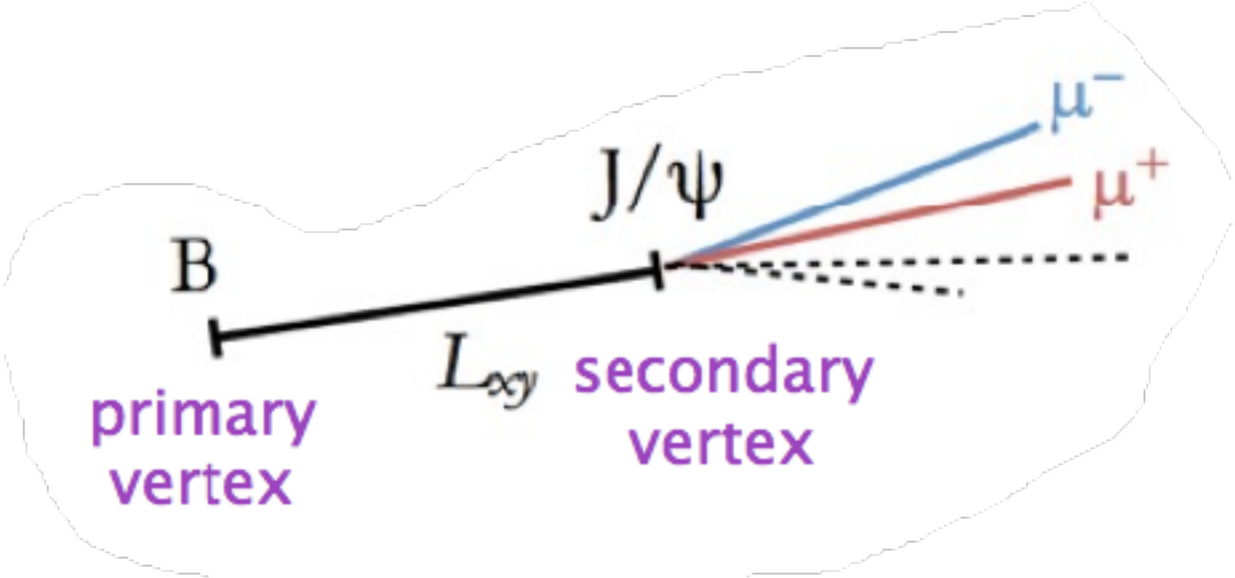
Table 11: Comparative overview of the models for heavy-quark energy loss or transport in the medium described in the previous sections.

Model	*Heavy-quark production*	*Medium modelling*	*Quark–medium interactions*	*Heavy-quark hadronisation*	*Tuning of medium-coupling (or density) parameter(s)*
Djordjevic *et al.* [511–515]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss finite magnetic mass	fragmentation	Medium temperature fixed separately at RHIC and LHC
WHDG [459, 519]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
Vitev et al. [422, 460]	non-zero-mass VFNS no PDF shadowing	Glauber model nuclear overlap ideal fl. dyn. 1+1d Bjorken expansion	radiative energy loss in-medium meson dissociation	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
AdS/CFT (HG) [624, 625]	FONLL no PDF shadowing	Glauber model nuclear overlap no fl. dyn. evolution	AdS/CFT drag	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
POWLANG [507–509, 585, 586]	POWHEG (NLO) EPS09 (NLO) PDF shadowing	2+1d expansion with viscous fl. dyn. evolution	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume pQCD (or l-QCD U potential)
MC@$_s$HQ+EPOS2 [528–530]	FONLL EPS09 (LO) PDF shadowing	3+1d expansion (EPOS model)	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at LHC, slightly adapted for RHIC
BAMPS [537–540]	MC@NLO no PDF shadowing	3+1d expansion parton cascade	transport with Boltzmann eq. rad. + coll. energy loss	fragmentation	RHIC (then scaled with $dN_{ch}/d\eta$)
TAMU [491, 565, 606]	FONLL EPS09 (NLO) PDF shadowing	2+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss diffusion in hadronic phase	fragmentation recombination	assume l-QCD U potential
UrQMD [608–610]	PYTHIA no PDF shadowing	3+1d expansion ideal fl. dyn.	transport with Langevin eq. collisional energy loss	fragmentation recombination	assume l-QCD U potential
Duke [587, 628]	PYTHIA EPS09 (LO) PDF shadowing	2+1d expansion viscous fl. dyn.	transport with Langevin eq. rad. + coll. energy loss	fragmentation recombination	QGP transport coefficient fixed at RHIC and LHC (same value)

[1506.03981]

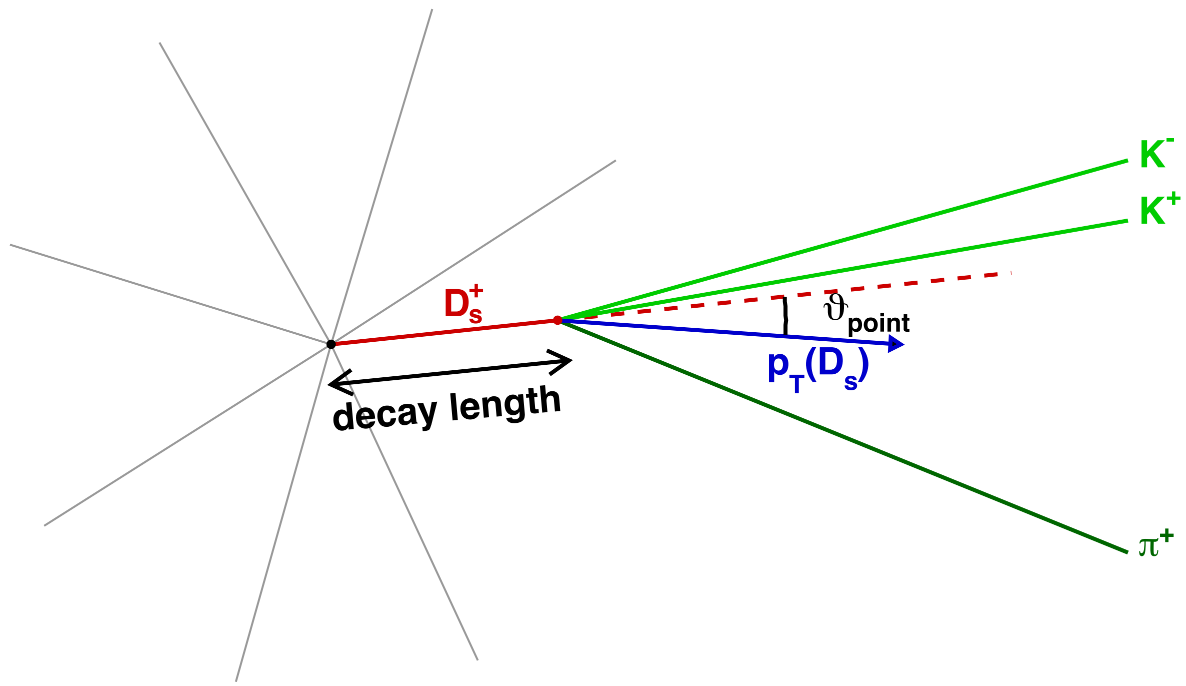
Our experimental tools





Displayed J/ψ from B decays

Semi-leptonic electrons and muons from c and b quarks



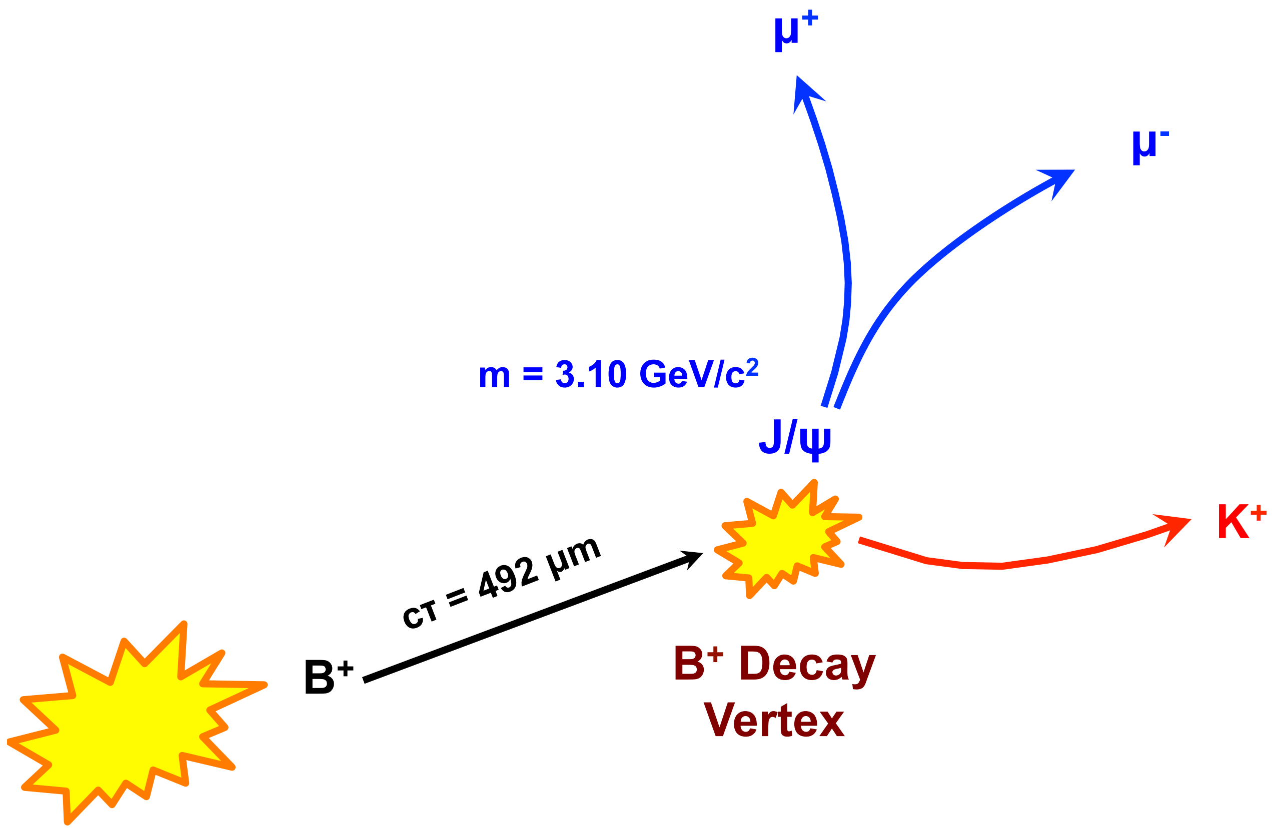
Fully reconstructed D meson decays:

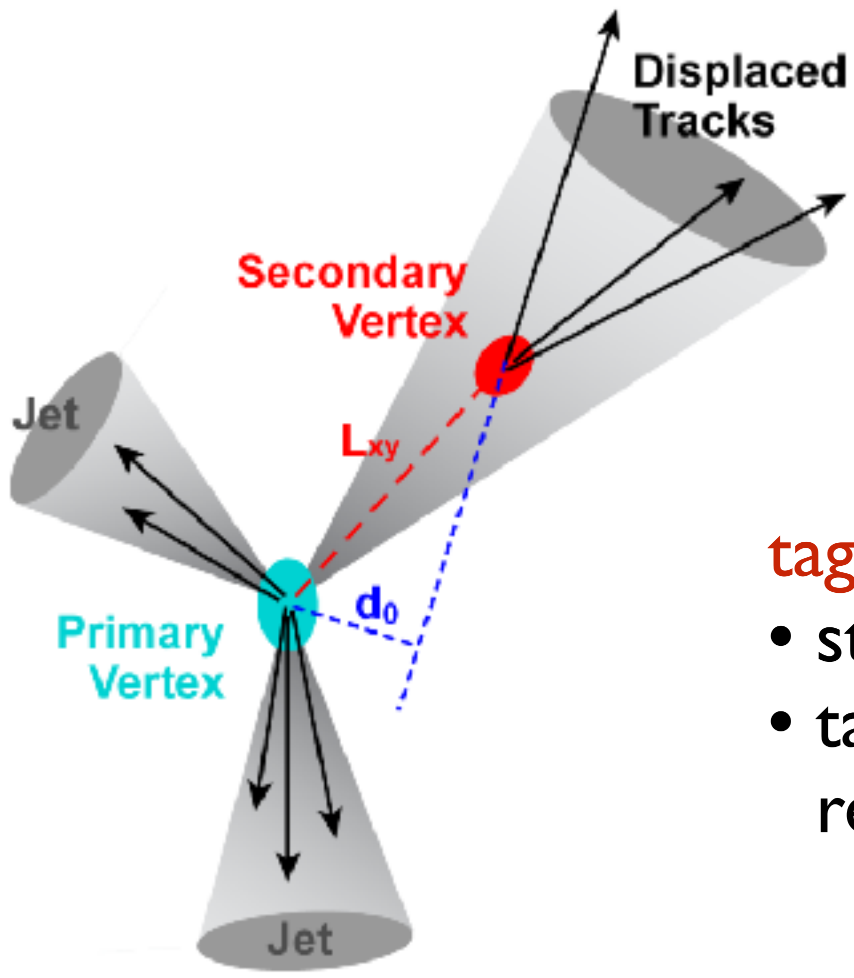
- $D^0 \rightarrow K^- + \pi^+$
- $D^+ \rightarrow K^- + \pi^+ + \pi^+$
- $D^{*+} \rightarrow D^0 + \pi^+$
- $D^+_s \rightarrow \phi + \pi^+$

Our experimental tools

Fully reconstructed B meson decays:

- $B^+ \to J/\psi\, K^+ \to \mu^+\mu^-\, K^+$
- $B^0 \to J/\psi\, K^{0*} \to \mu^+\mu^-\, K^+\pi^-$
- $B_s \to J/\psi\, \phi \to \mu^+\mu^-\, K^+K^-$





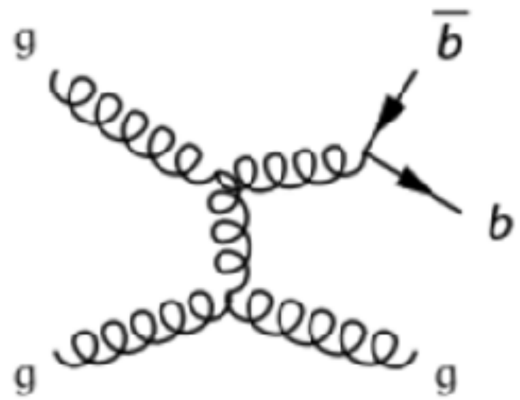
tagged c- and b-jets

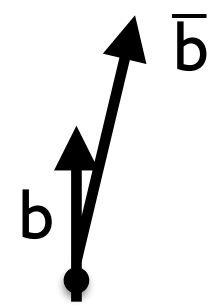
- standard jet reconstruction
- tagging based on the displacement with respect to the primary vertex

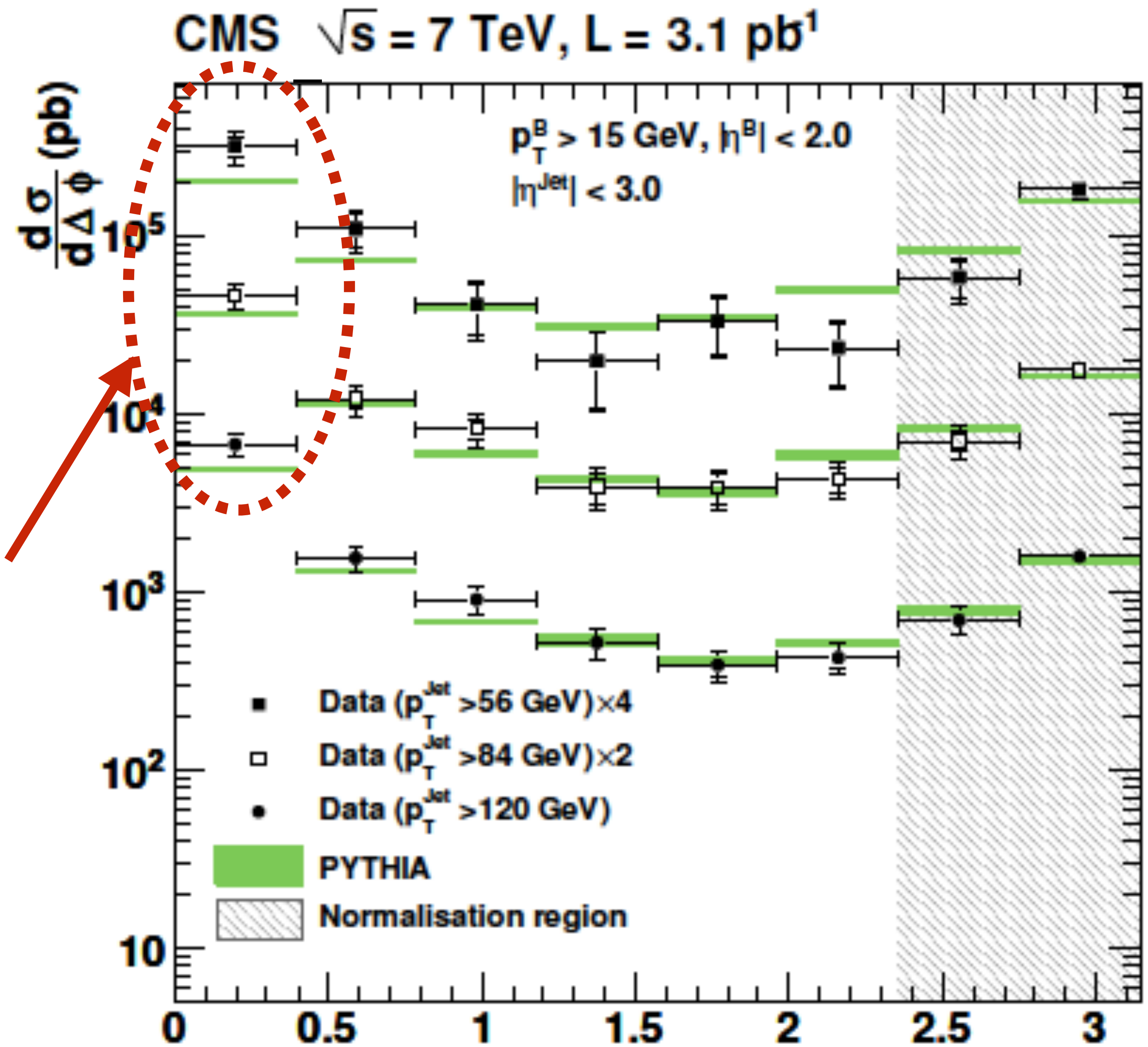
$B\bar{B}$ $\Delta\phi$ correlations

NLO process: Gluon splitting (GSP)

→ produced with small opening angles and asymmetric in p_T



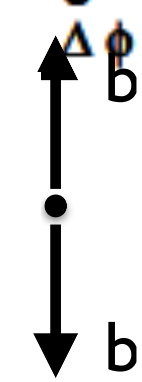




JHEP 1103:136,2011

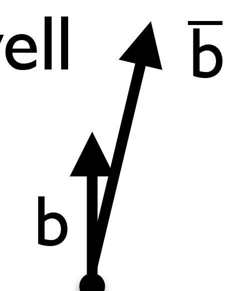
$B\bar{B}$ correlations strongly affected by gluon splitting processes at low $\Delta\phi$

$\Delta\phi(B\text{-}\bar{B})$



Gluon splitting (GS) contribution not well modelled by most of the calculations

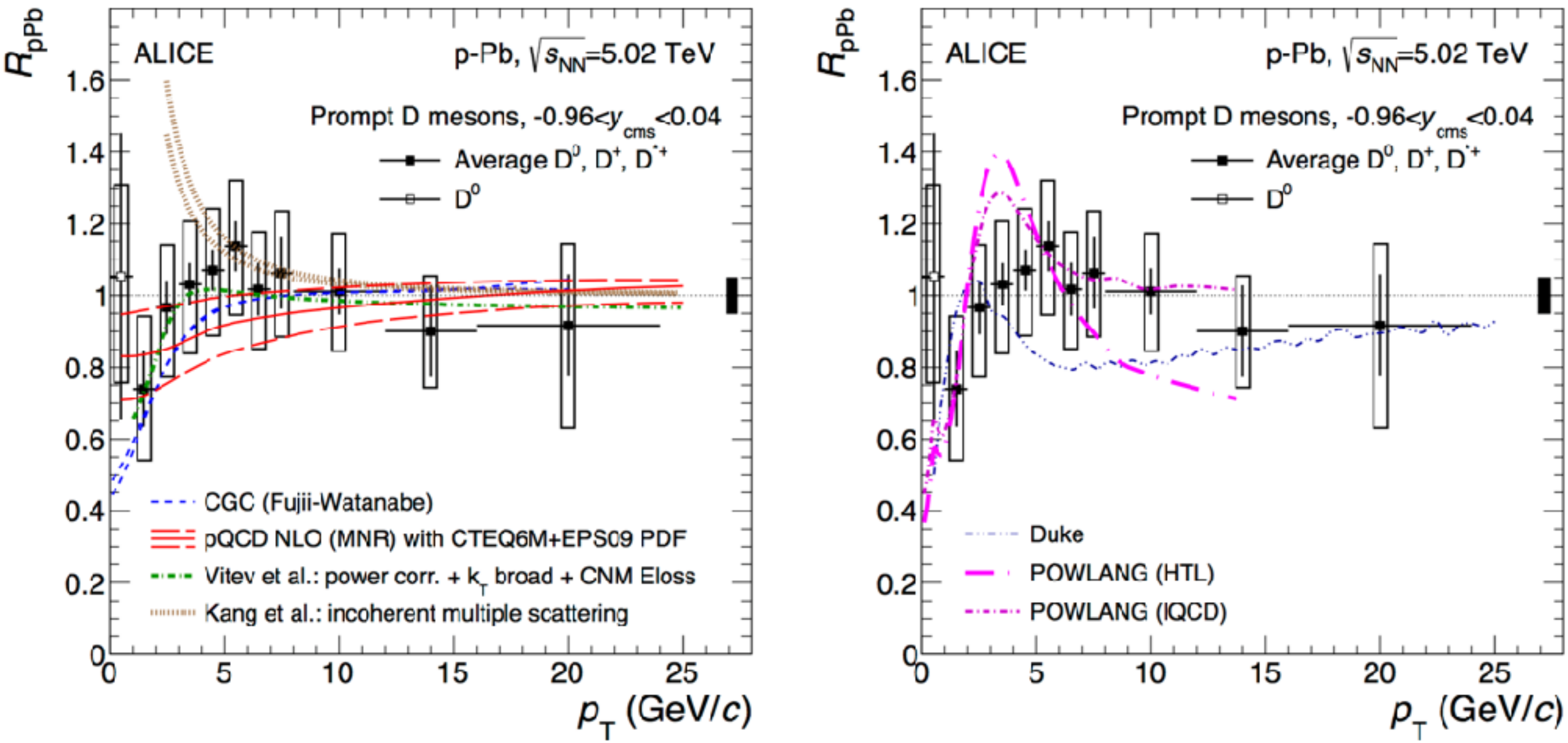
→GS contribution underestimated by models



D^0 production in pPb collisions

ALICE D measurements at 5.02 TeV, |y|<0.5

ALICE, arXiv:1605.07569

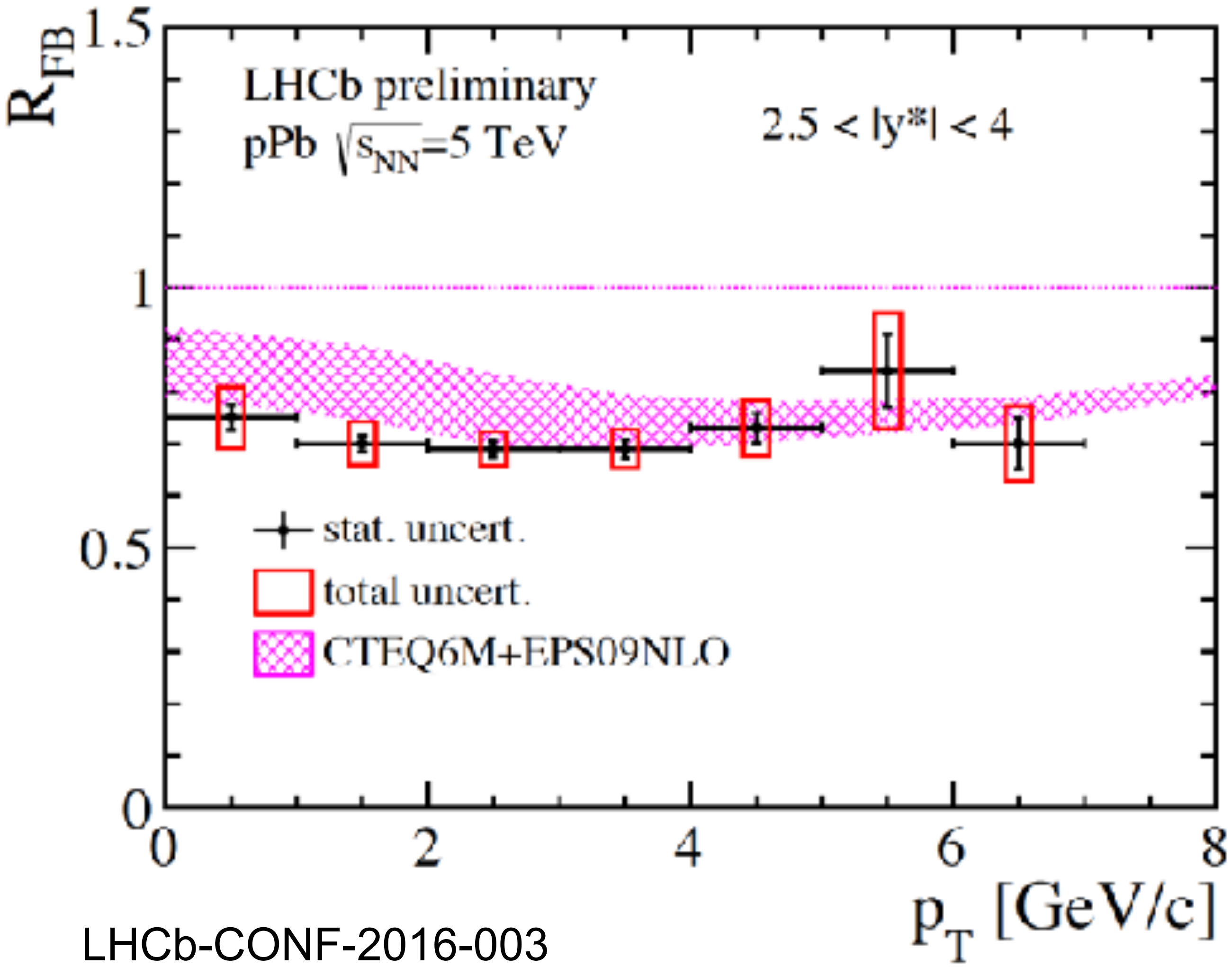


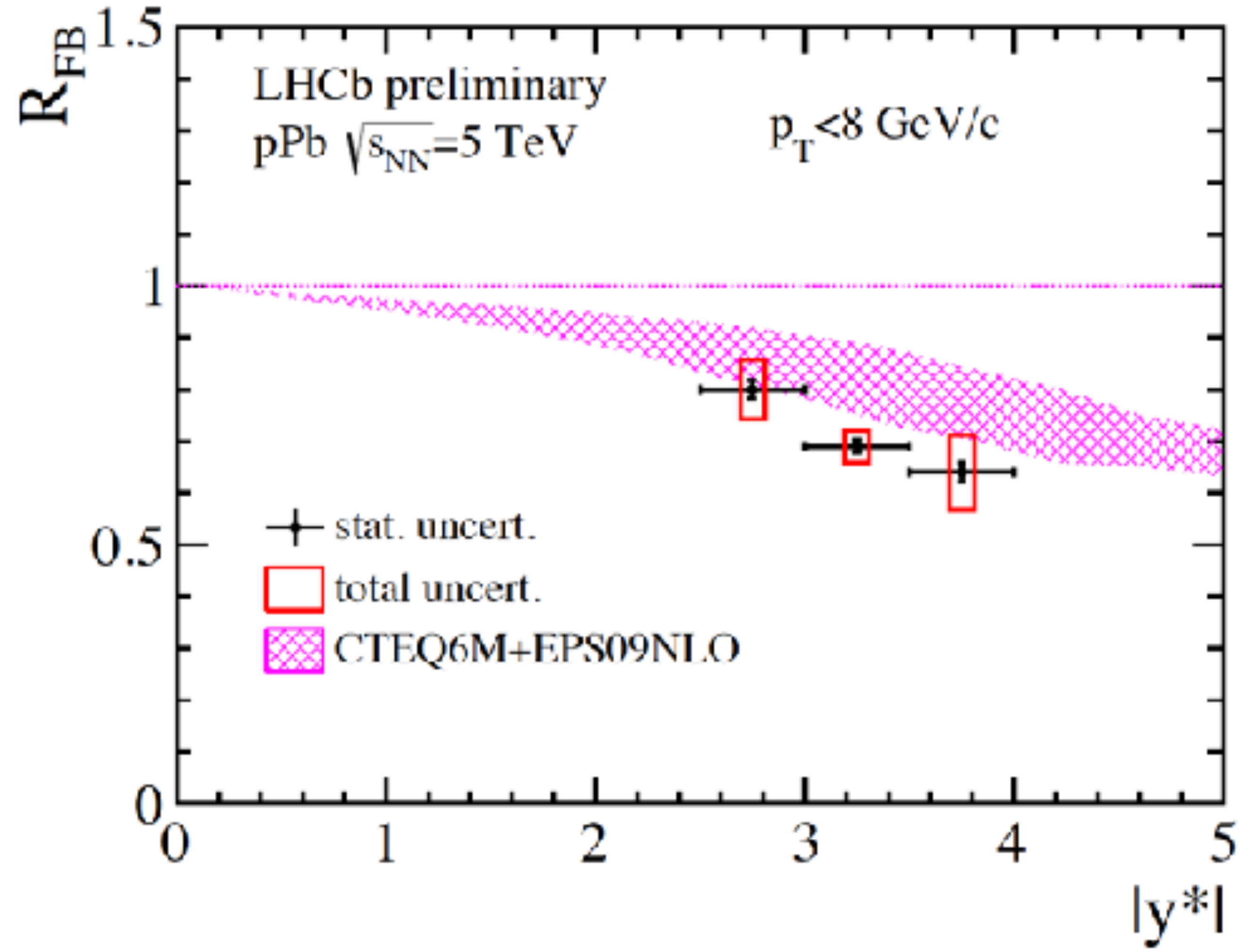
R_{pA} well described by Cold Nuclear Matter (CNR) models and consistent with unity at high p_T!

Not possible to discriminate between various models with current uncertainties

D^0 meson R_{pA} at 5.02 TeV

LHCb D^0 measurement at 5.02 TeV in forward(F) and backward (B) region as a function of transverse momentum and rapidity

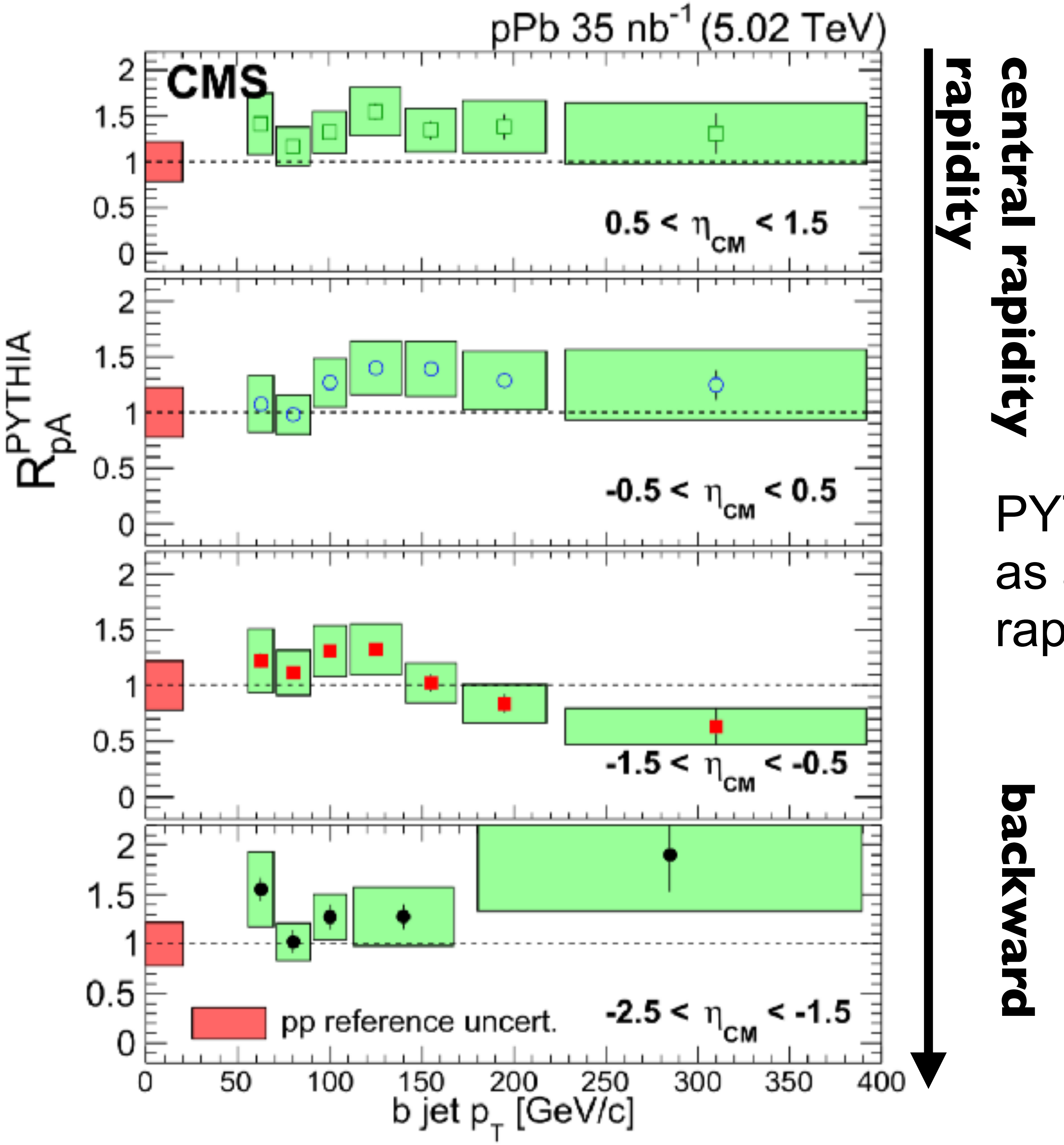




LHCb-CONF-2016-003

R_{pA} and R_{FB} described by to NLO prediction that include EPS09 parametrisation of the nuclear PDFs

b-jet nuclear modification factor in pPb



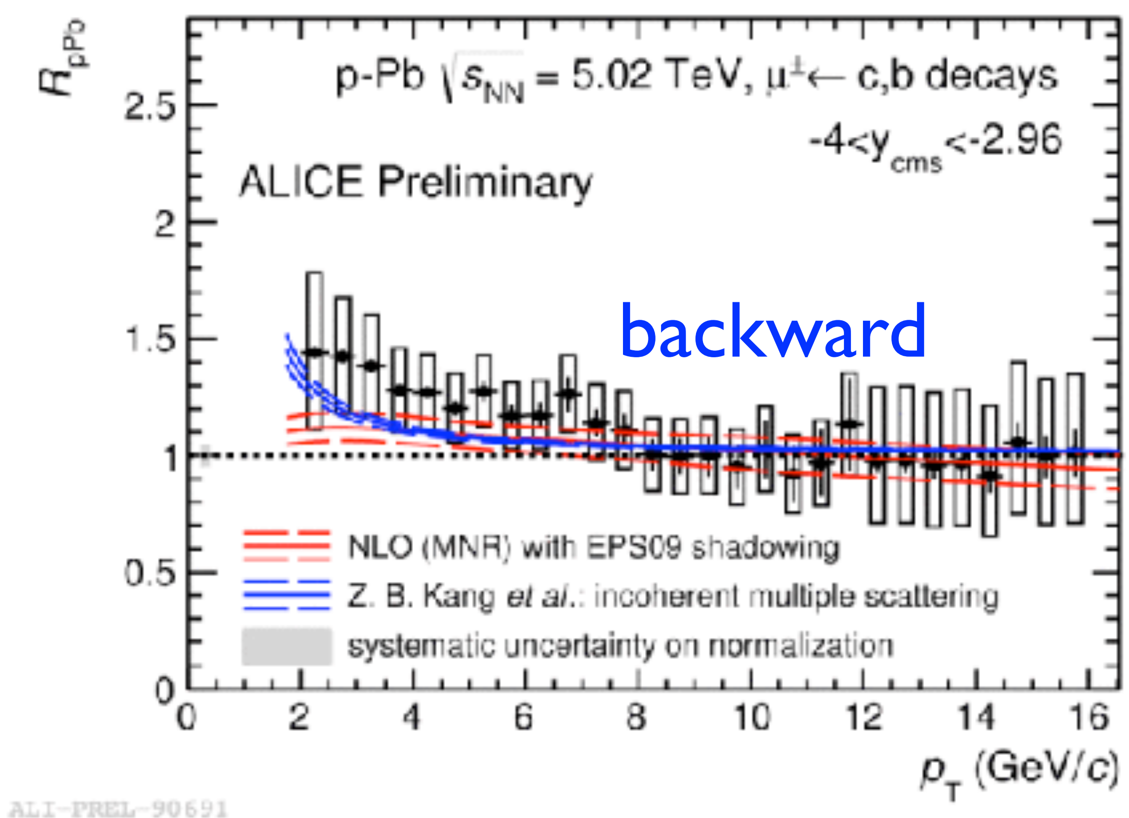
CMS b-jet R_{pA} in bins of transverse momentum and pseudo-rapidity

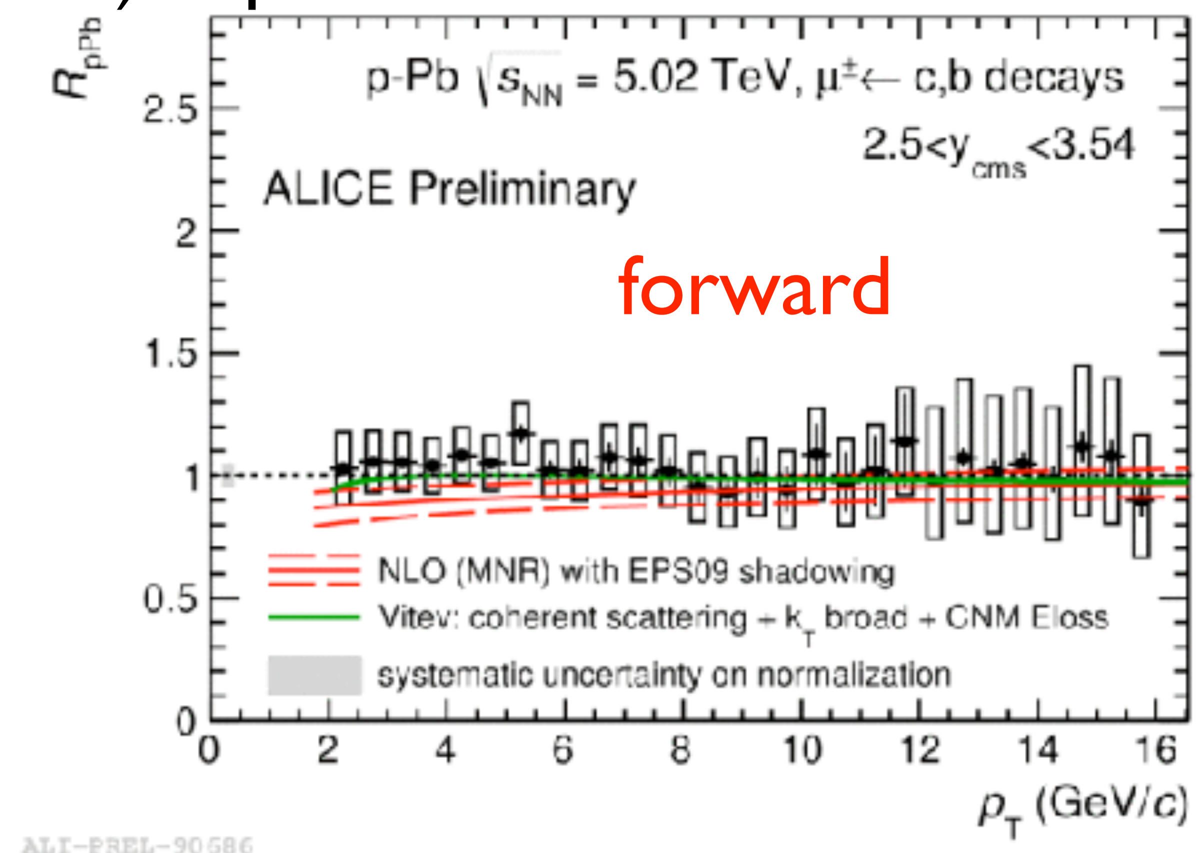
PYTHIA R_{pA} consistent with unity as a function of p_T and pseudo-rapidity

CMS, PLB 754 (2016) 59

Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons (c,b→muons) in pPb collisions at 5.02 TeV





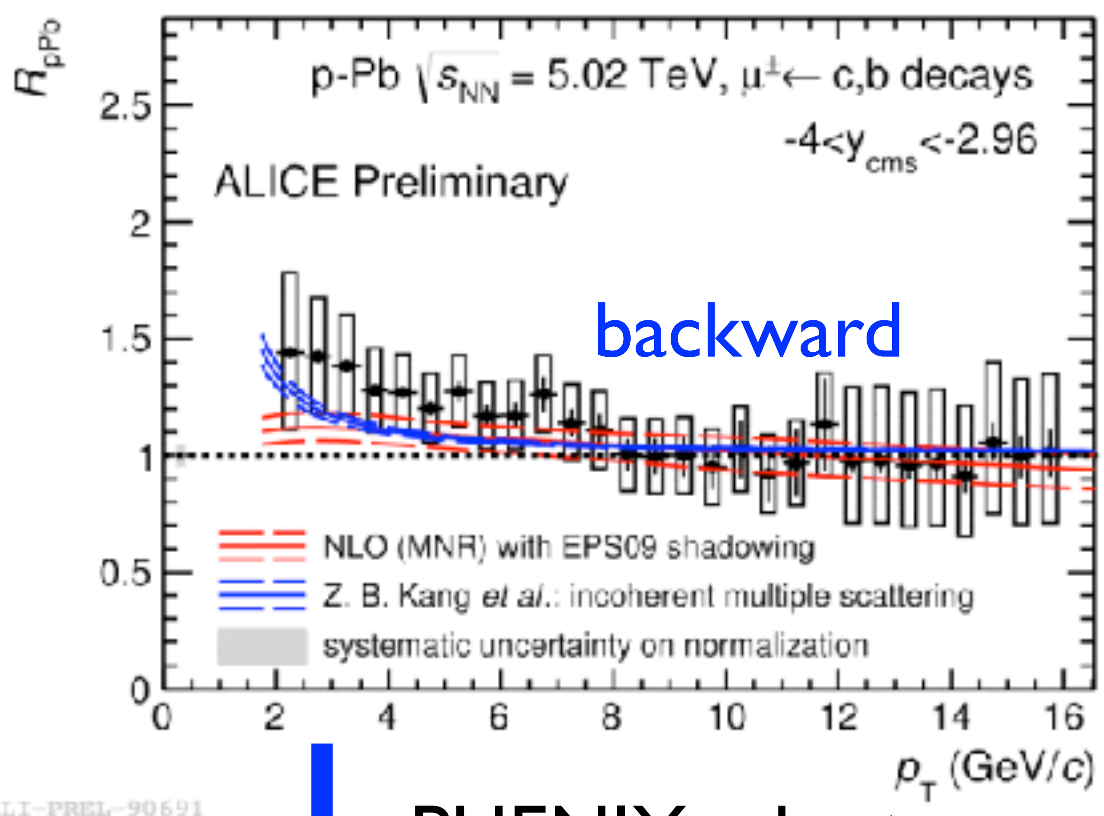
forward (shadowing)
backward (anti-shadowing)

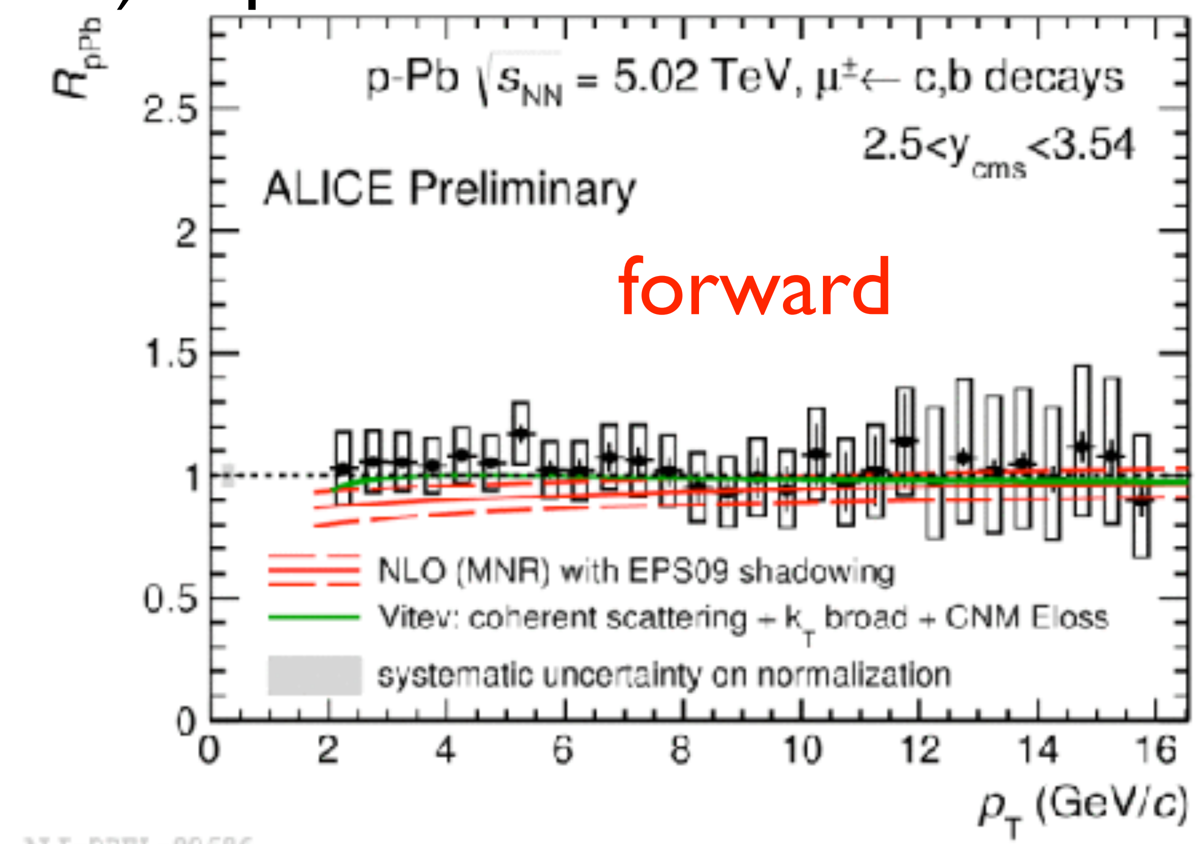
Models with CNM describe forward/backward rapidity at LHC

PRL112 (2014) 252301

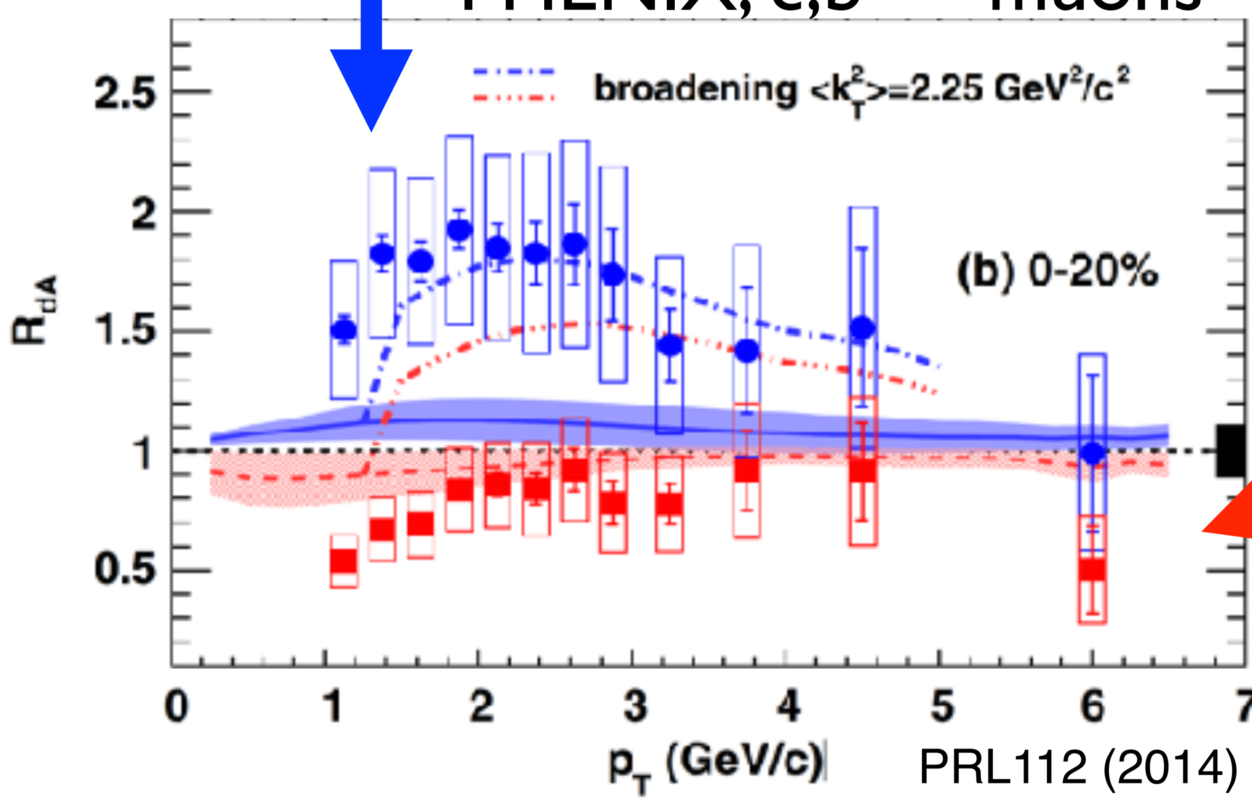
Heavy flavour leptons: LHC vs. RHIC

ALICE heavy flavour muons (c,b→muons) in pPb collisions at 5.02 TeV





PHENIX, c,b → muons



PRL112 (2014) 252301

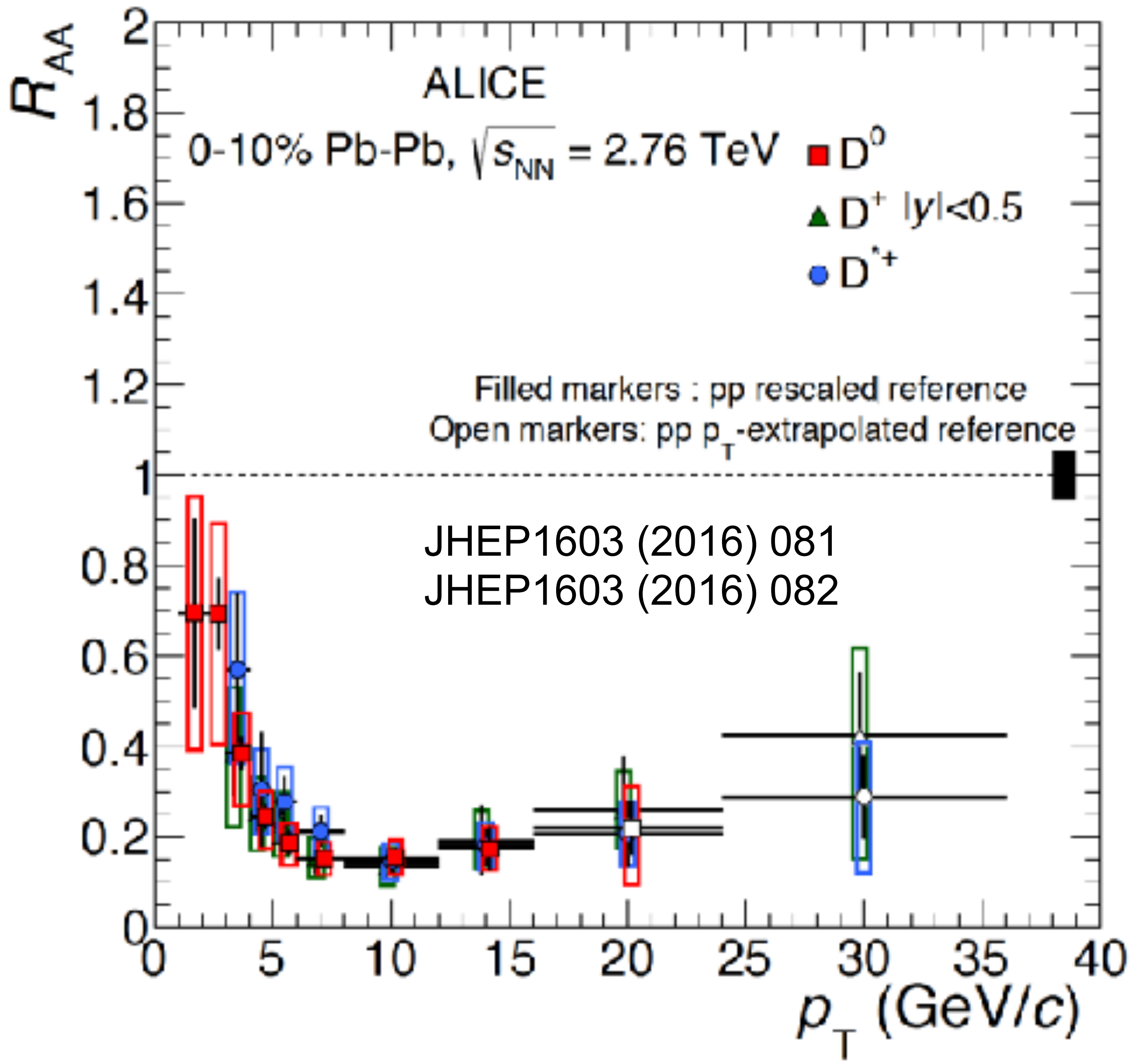
forward (shadowing)
backward (anti-shadowing)

Models with CNM describe forward/backward rapidity at LHC

→ **Not possible at RHIC**

D meson R_{AA} in 0-10%

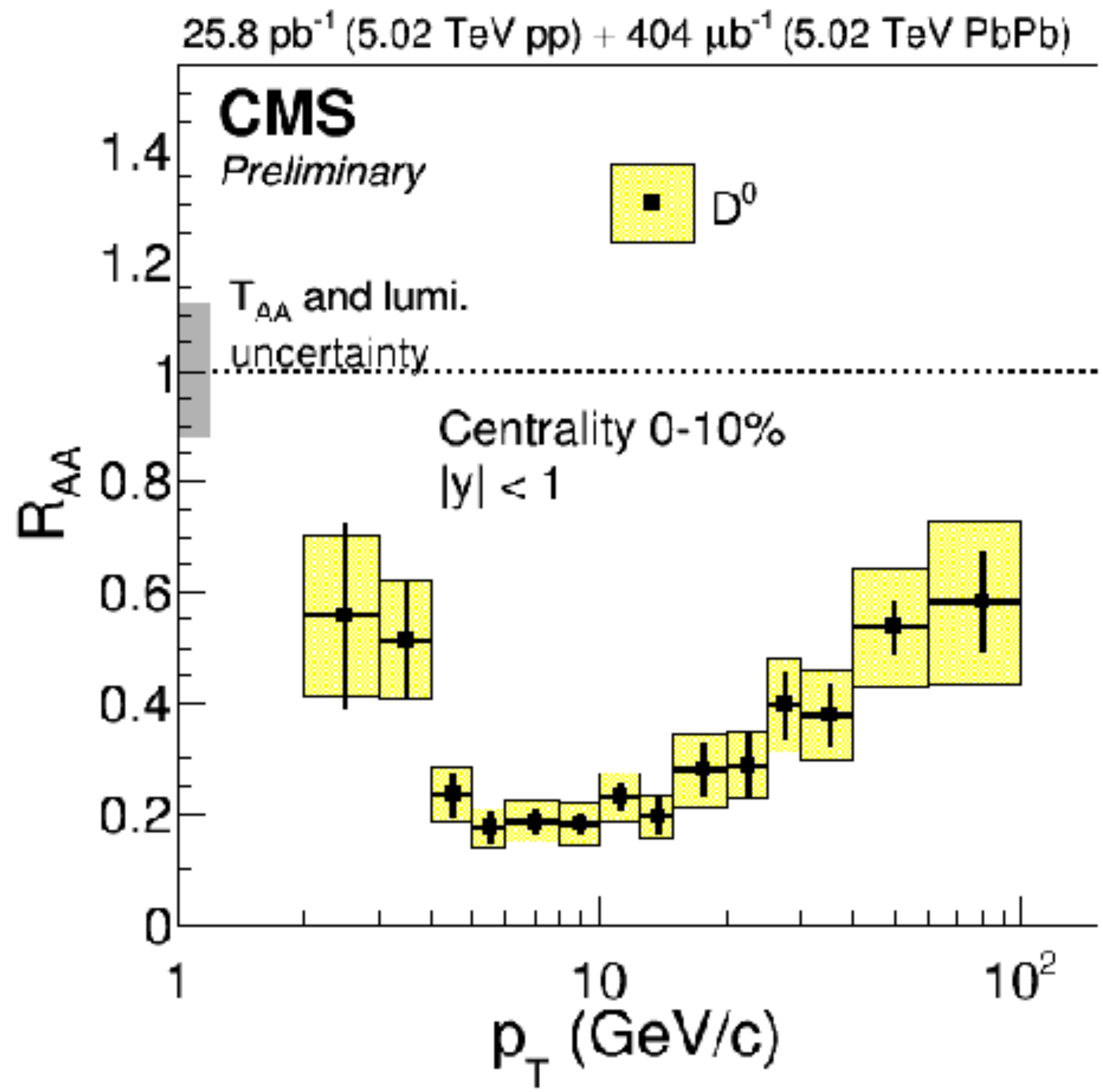
ALICE D^0 R_{AA} **|y|<0.5** at **2.76 TeV**



Strong suppression at 2.76 TeV:

same suppression for D^0,D^+,D^{*+}

CMS D^0 R_{AA} **|y|<1.0** at **5.02** TeV

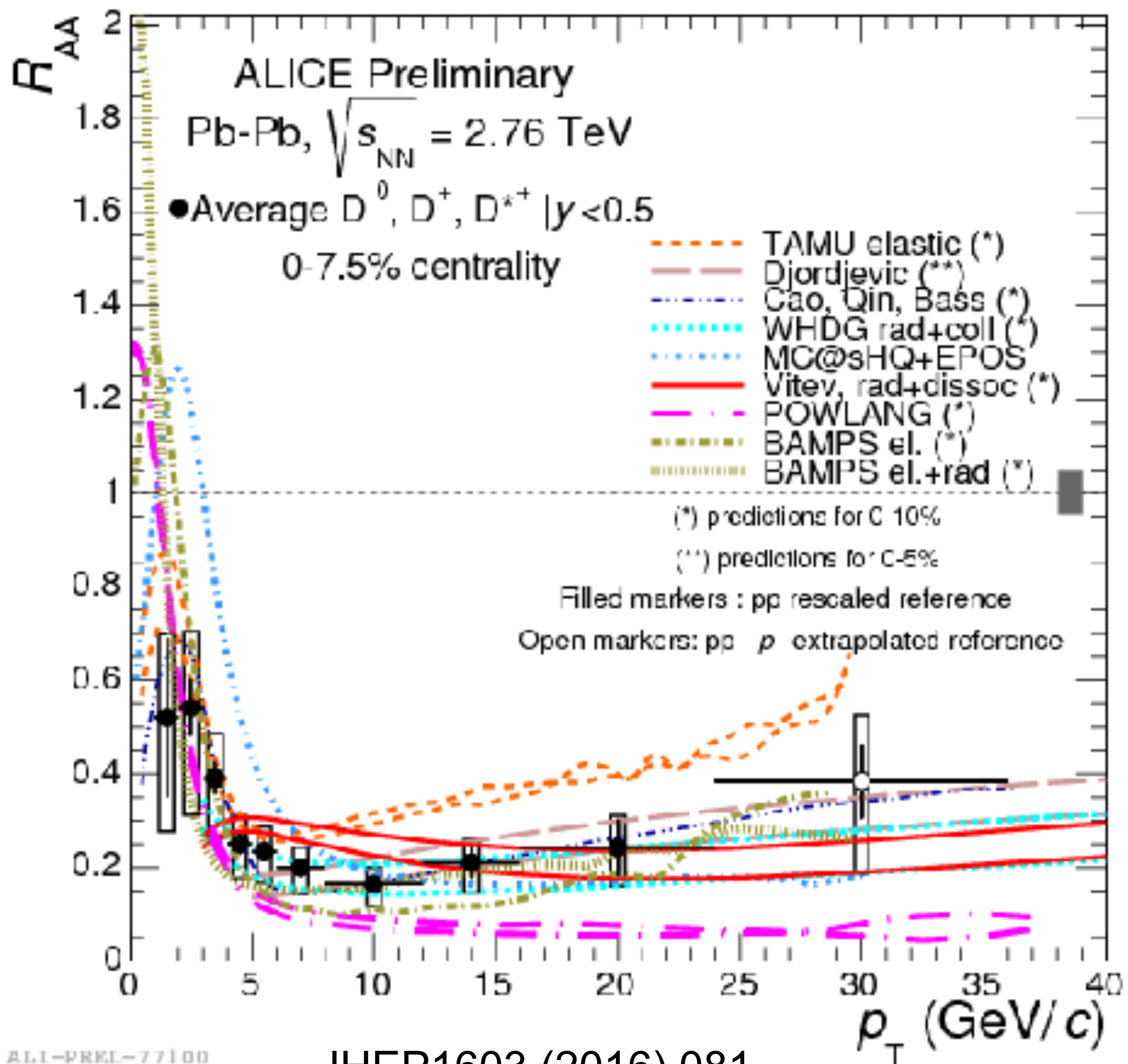


CMS-PAS-HIN-16-001

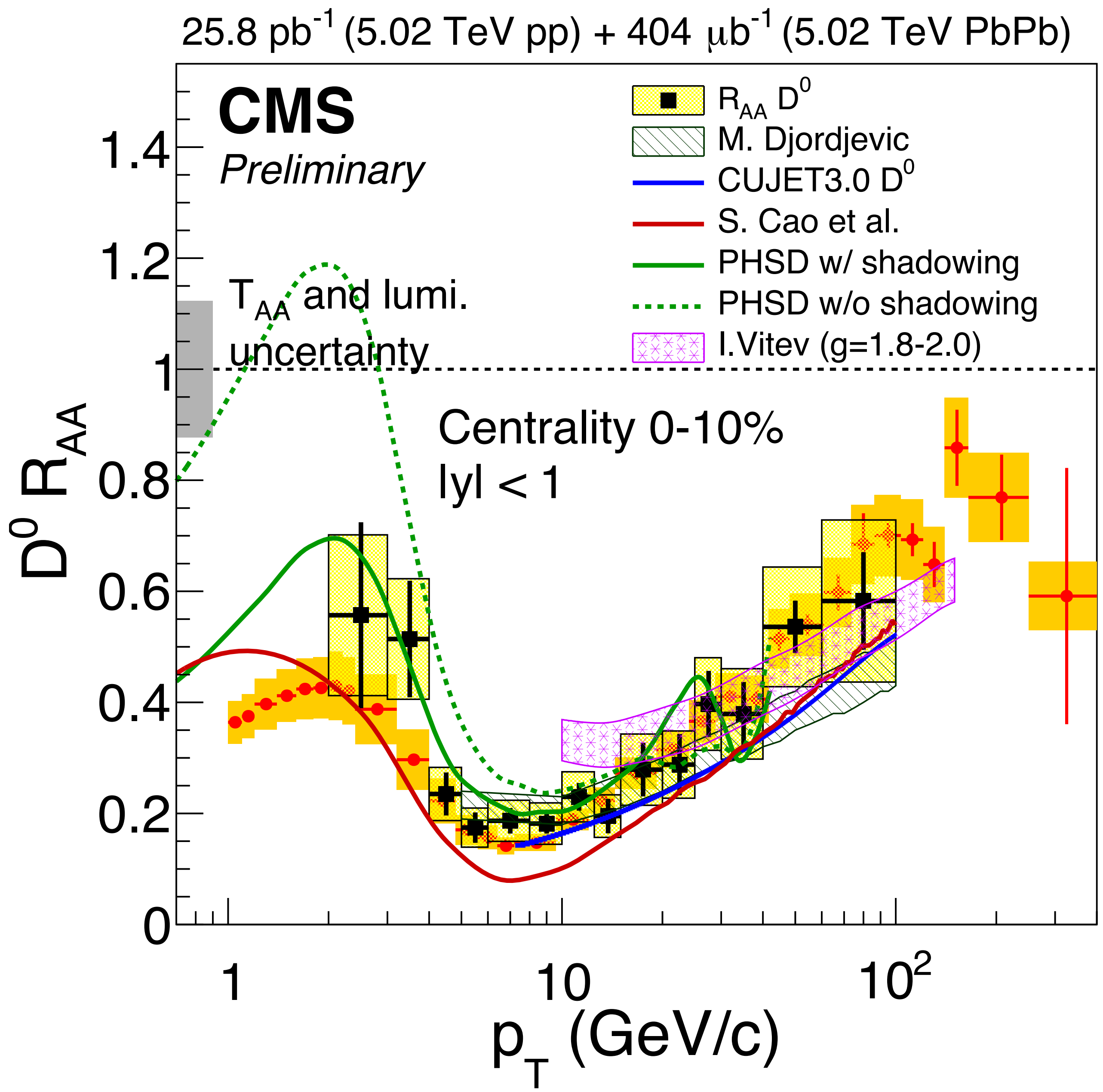
Similar suppression at 5.02 TeV:

Rising trend observed when going to high p_T

Comparison to theoretical calculations



JHEP1603 (2016) 081
JHEP1603 (2016) 082

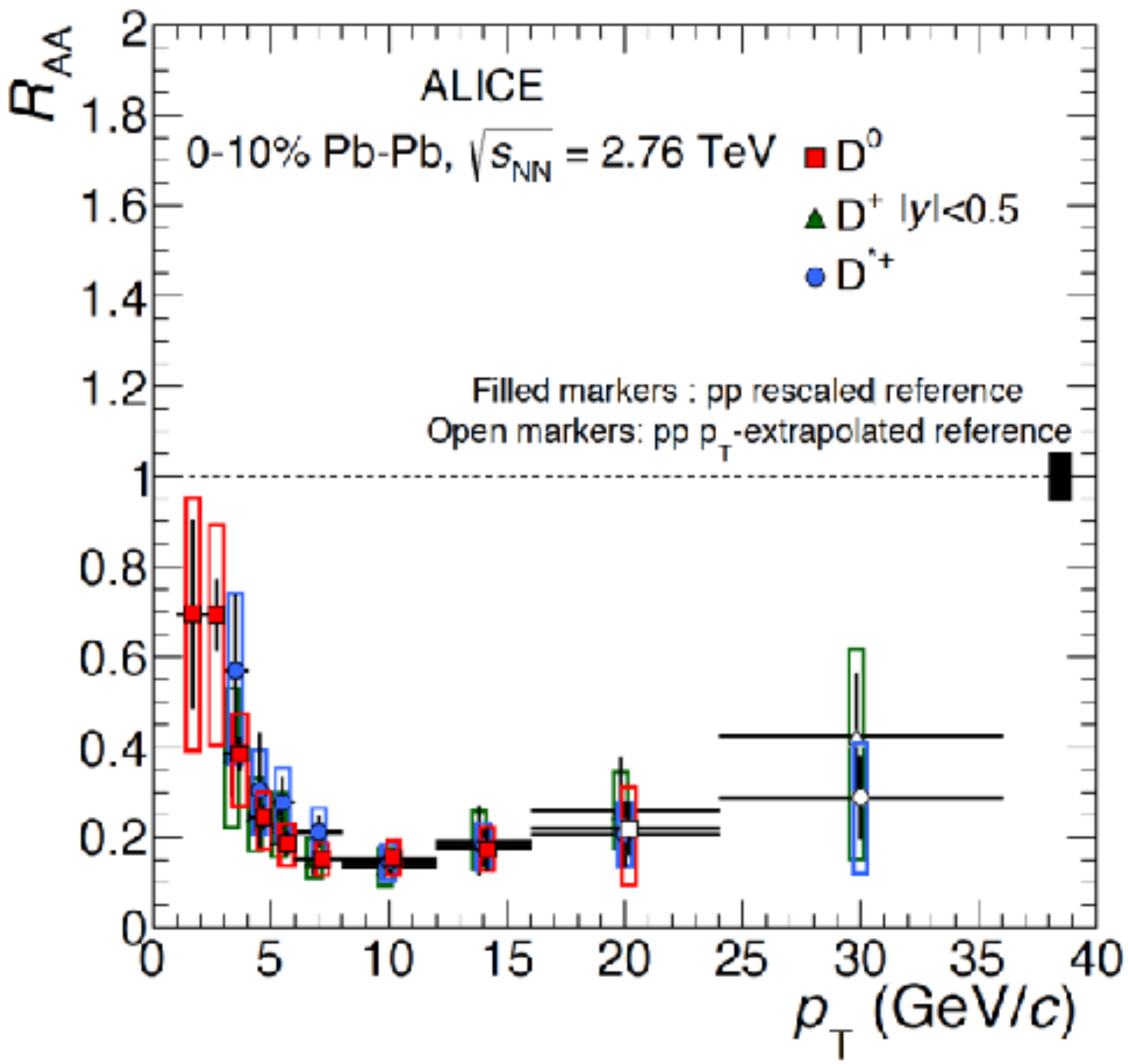


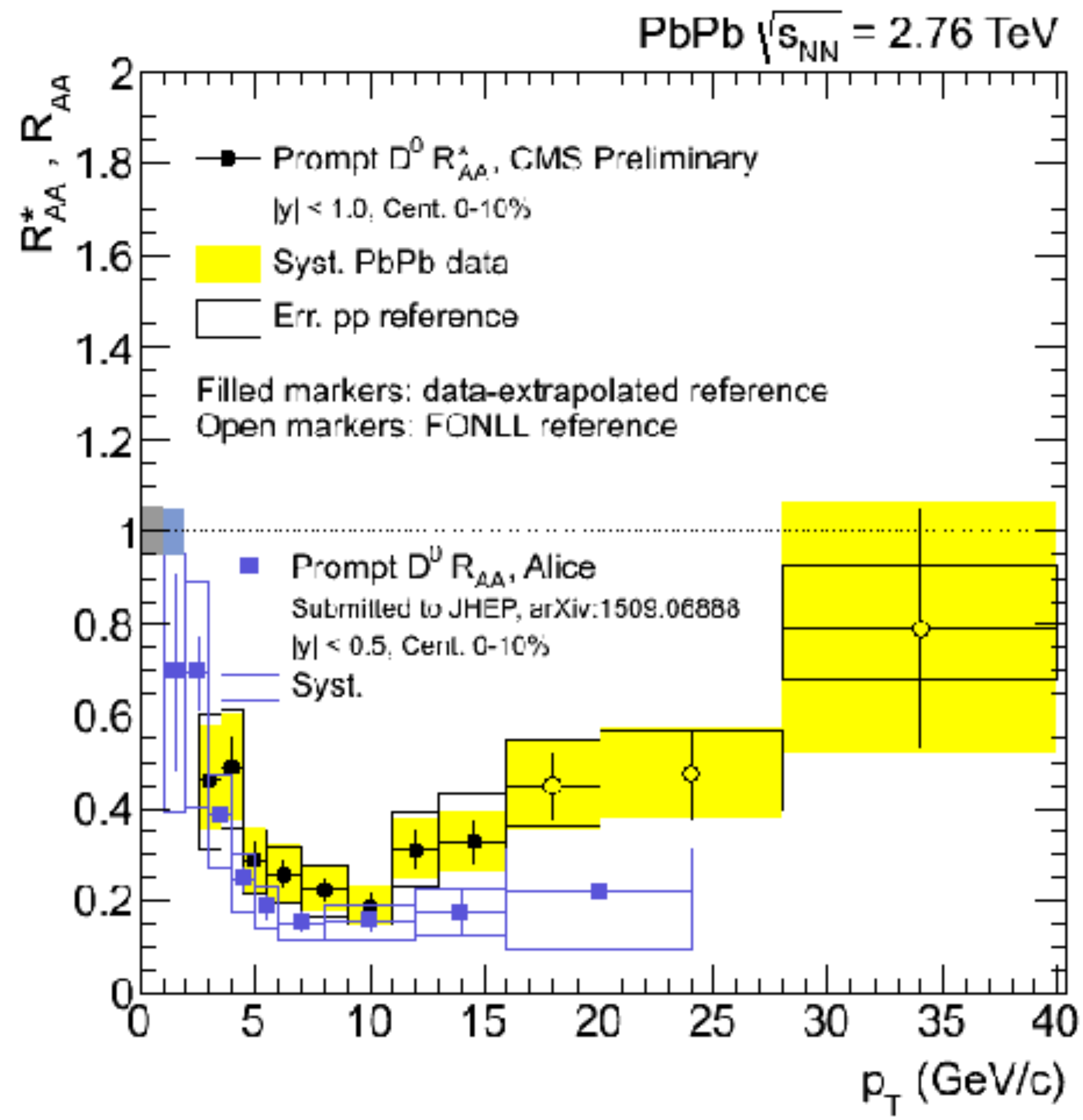
CMS-PAS-HIN-16-001

Several models describe the data within uncertainties:

- *hints at low p_T that collisional energy loss is non negligible*
- *pure collisional models can describe the R_{AA} up to high p_T (??)*
- *shadowing improve description of the data at low p_T*

D meson R_{AA} at 2.76 TeV





Strong suppression in central PbPb events:

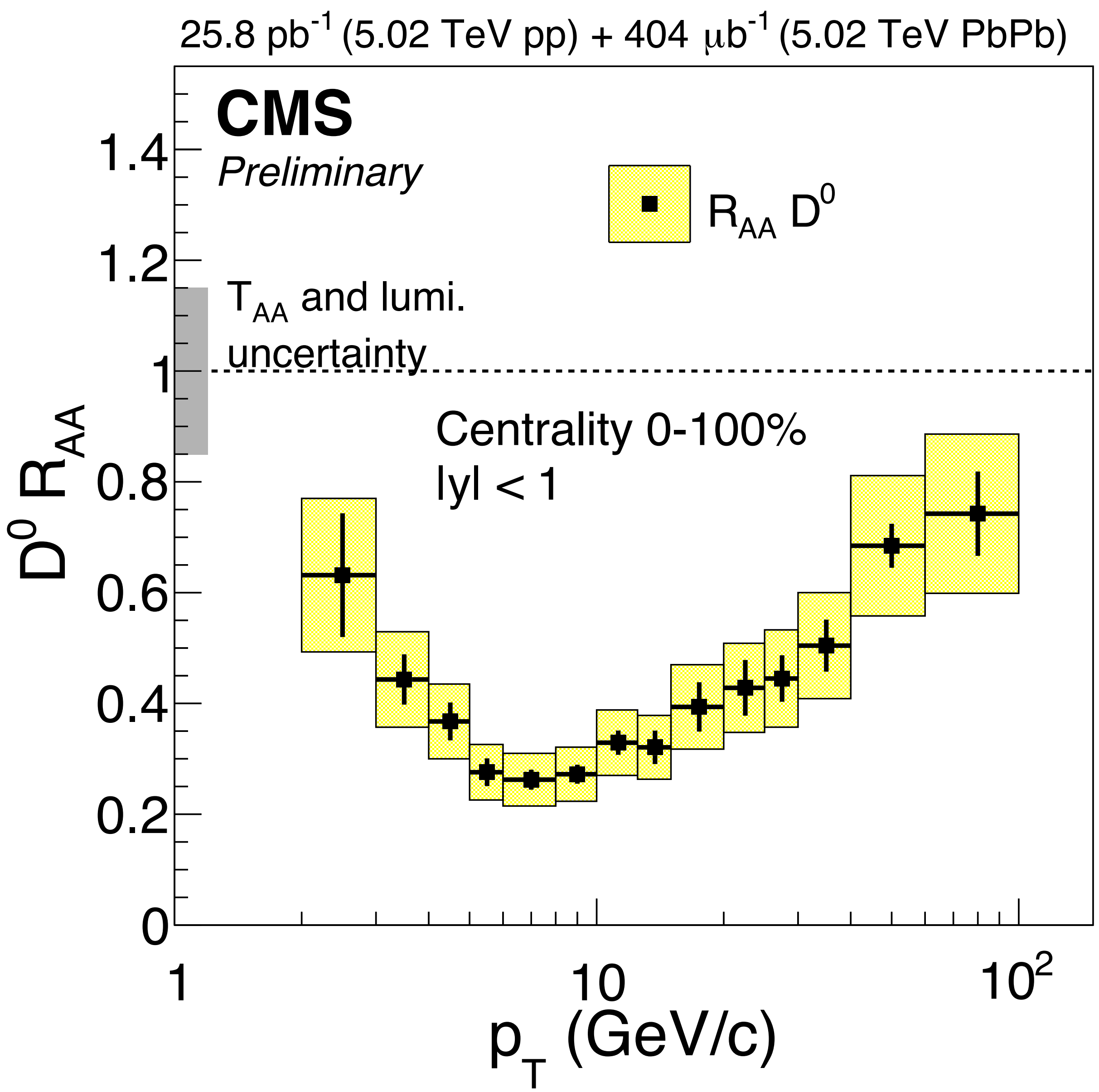
same suppression for D^0,D^+,D^{*+} indicate independence from fragmentation

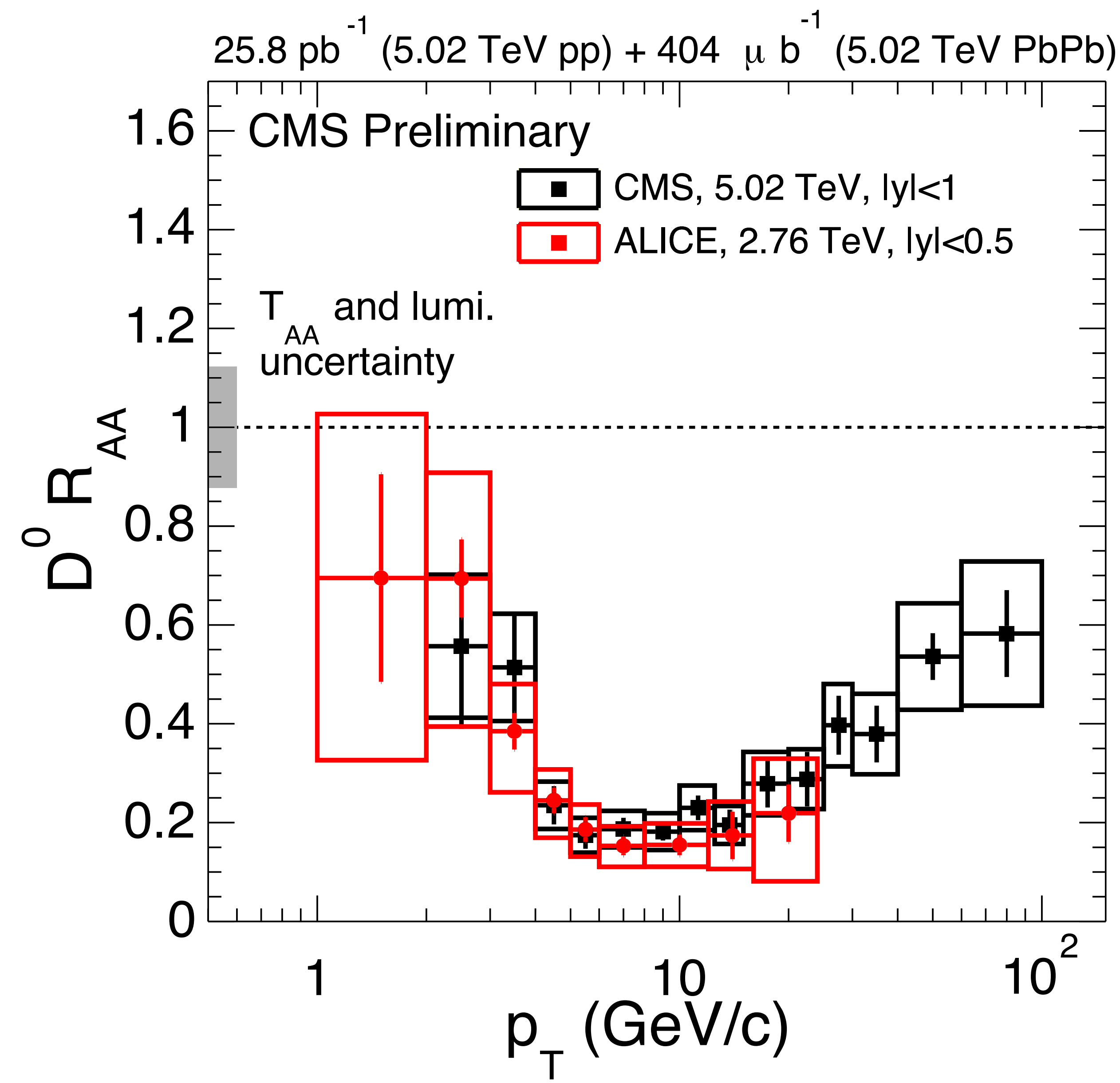
ALICE and **CMS** in good agreement

Differences at higher p_T due to different pp references

D^0 meson R_{AA} at 5.02 TeV

CMS D^0 R_{AA} |y|<1.0 at 5.02 TeV





Strong suppression observed at 5.02 TeV

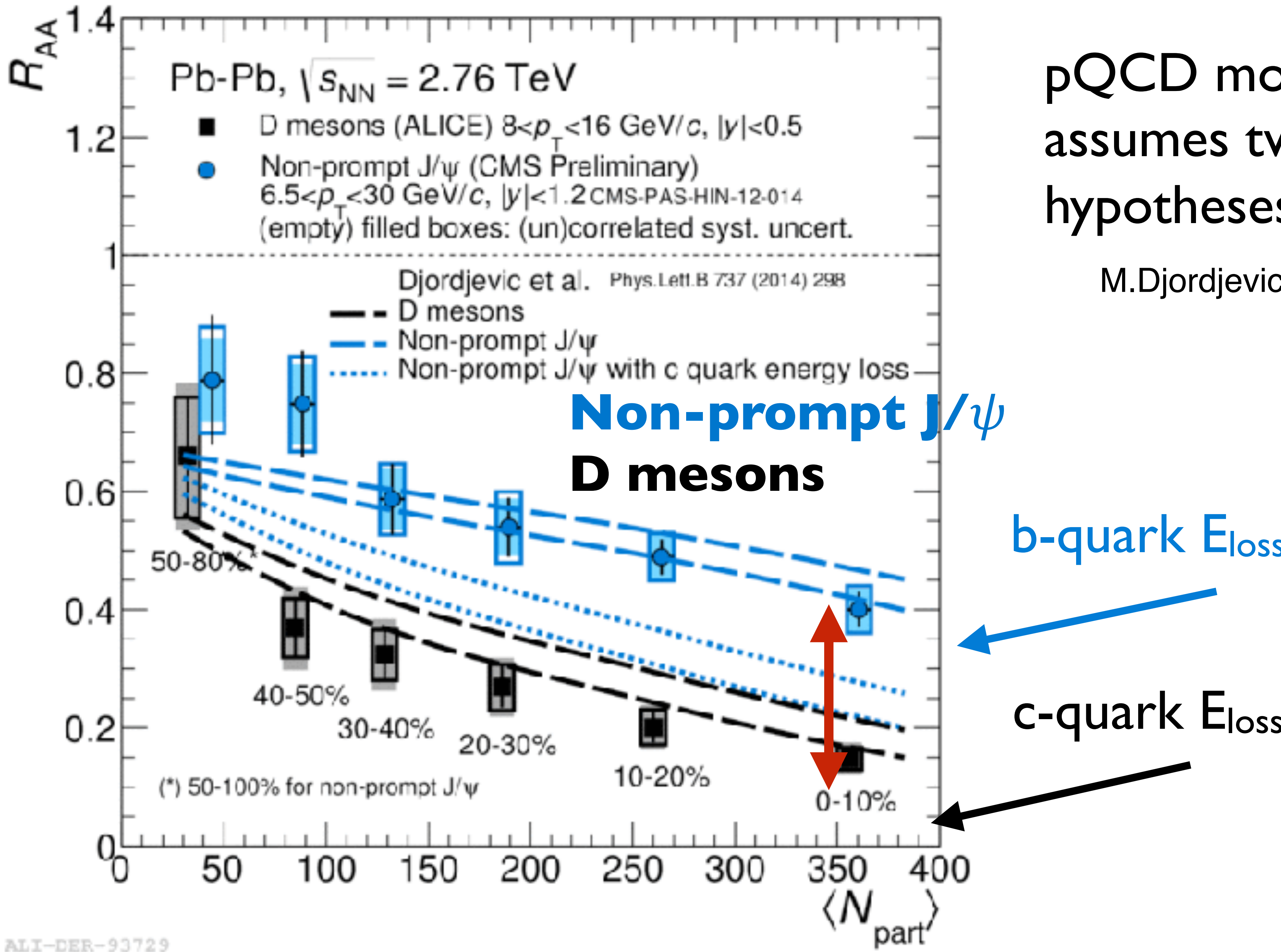
Rising trend observed when going to high p_T

Similar suppression observed at 2.76 and 5.02 TeV by CMS and ALICE

Caveat: different rapidities

Flavour dependence of E_{loss} at 2.76 TeV

ALICE, JHEP 1511 (2015) 205



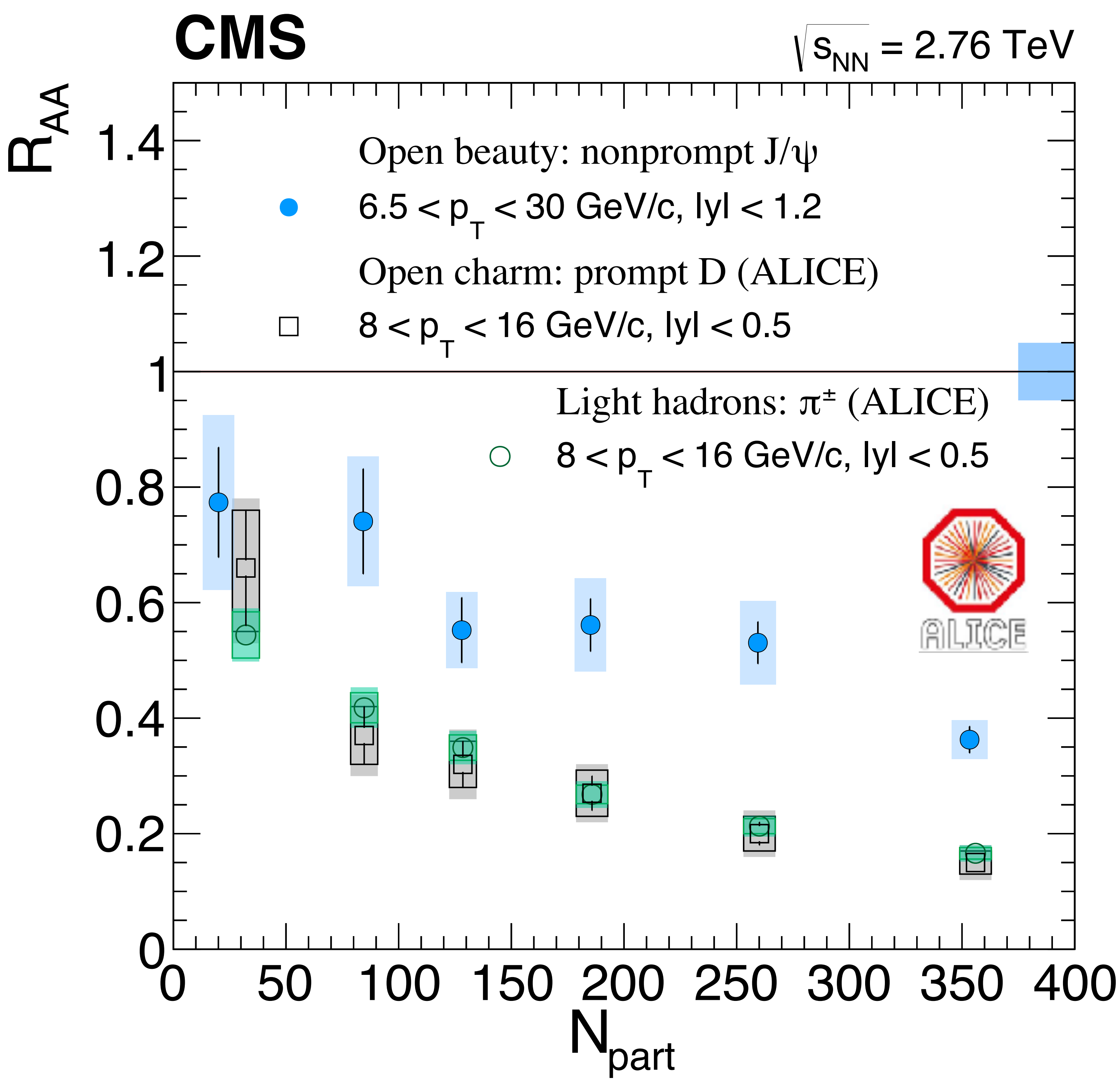
pQCD model (M.Djordjevic) that assumes two different mass hypotheses for non prompt J/ψ

M.Djordjevic, PRL 112, 042302 (2014)

***According to this model**, the difference R_{AA} for non prompt J/ψ and B can be attributed to a difference in the E_{loss} of charm and beauty quarks*

Flavour dependence of E_{loss} at 2.76 TeV

CMS-PAS-HIN-15-005



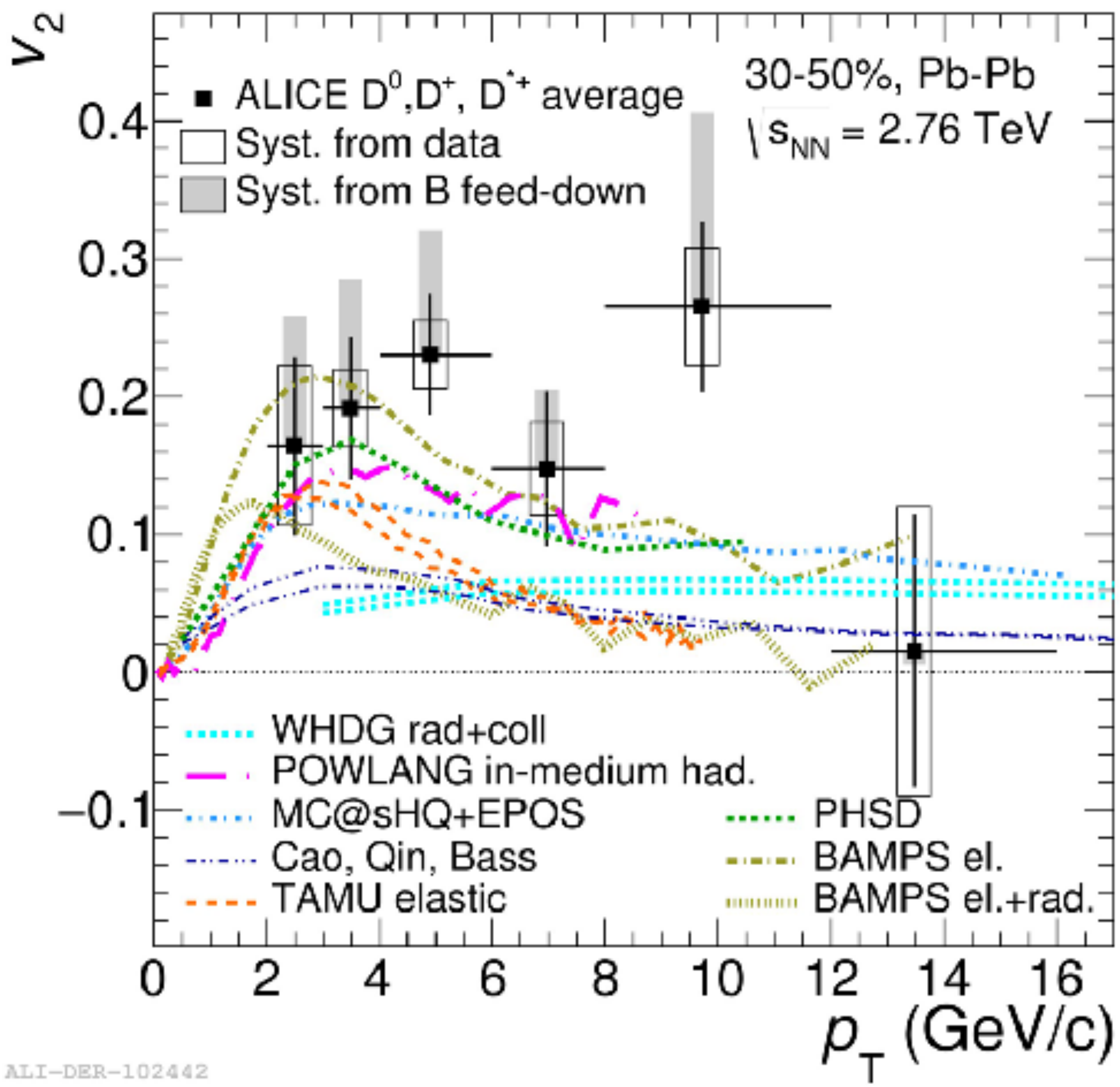
Non-prompt J/ψ

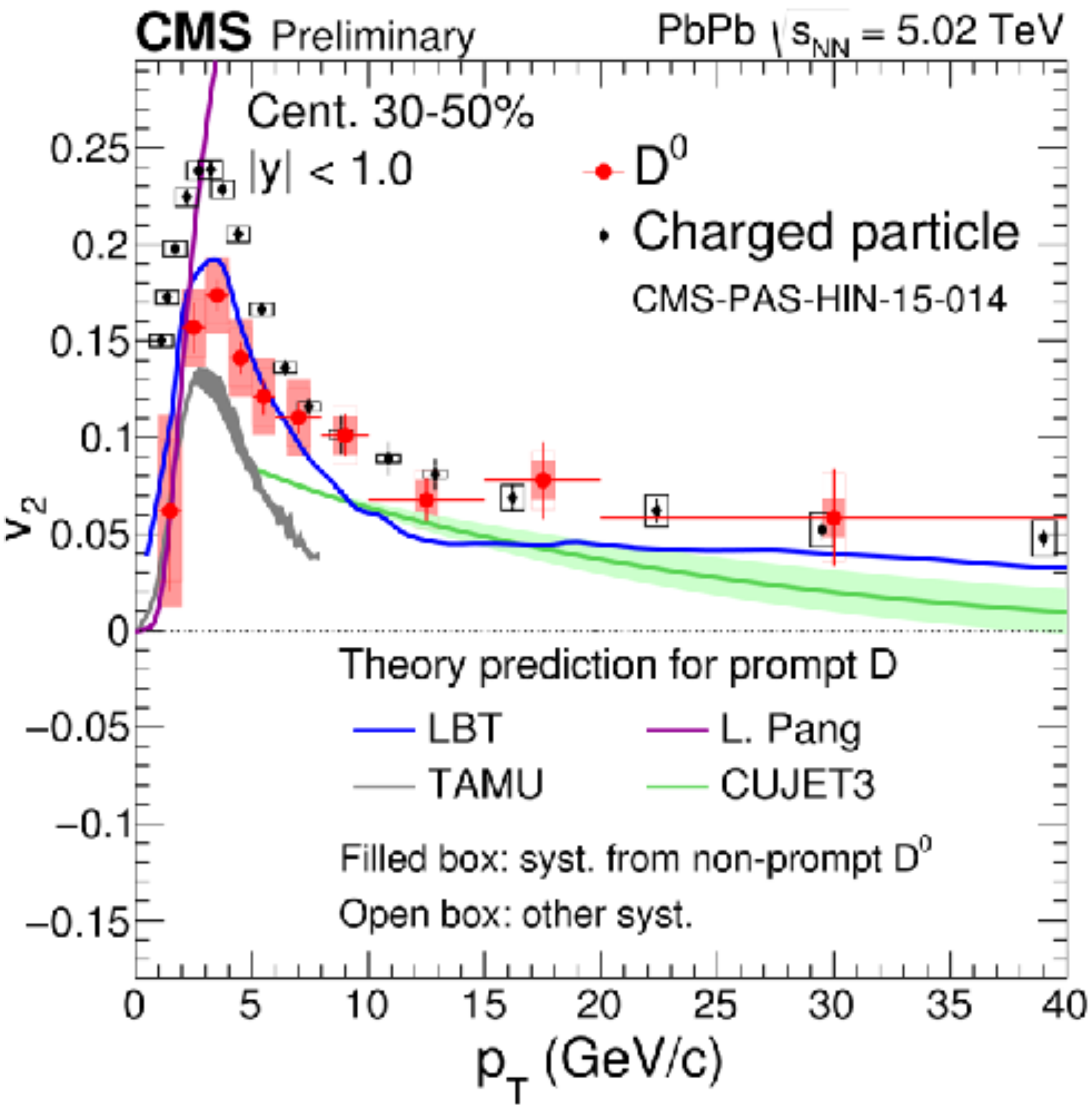
D mesons

π^{+-}

No change in the physics message when comparing to the final result of non prompt J/ψ R_{AA} from CMS

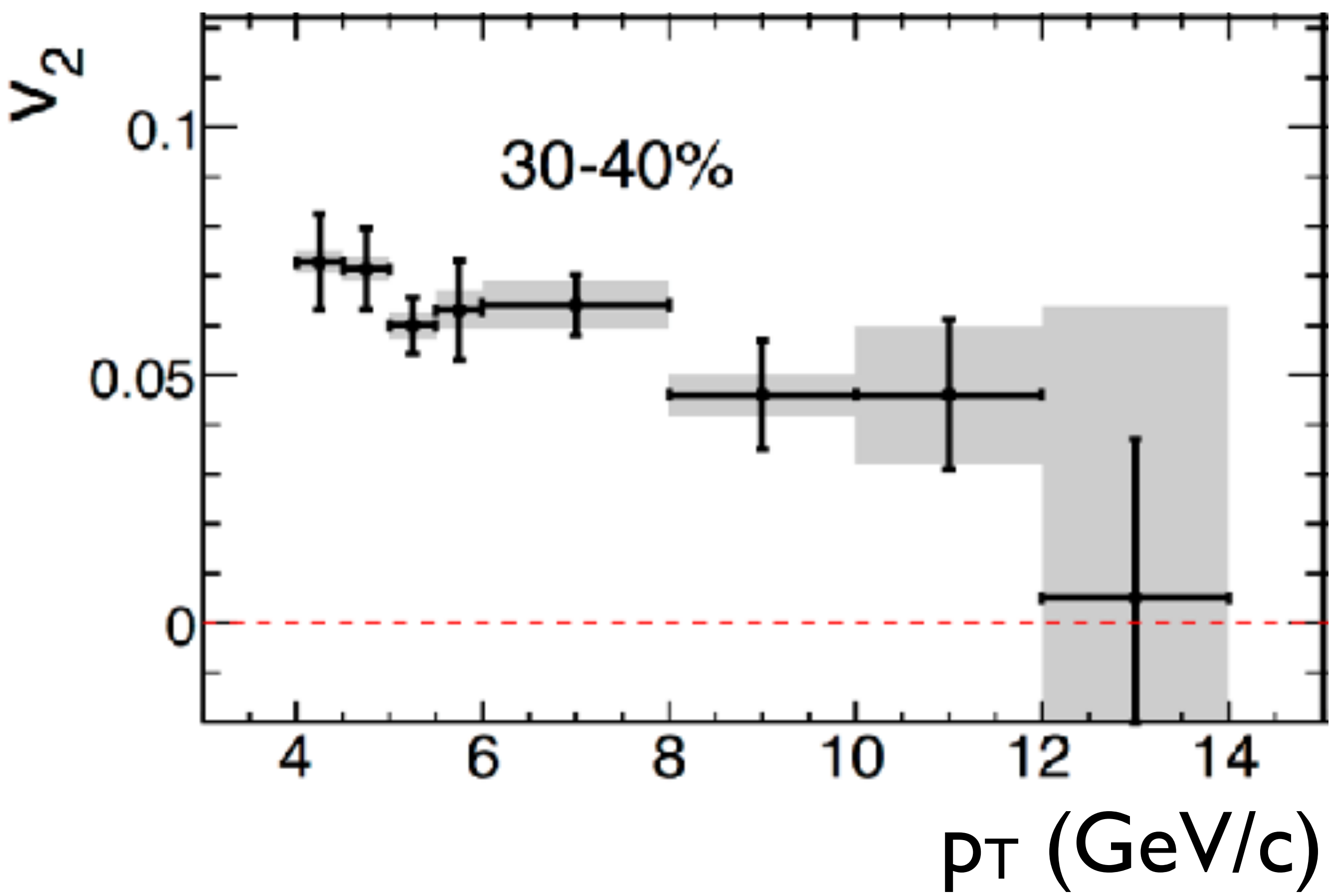
Comparison with models

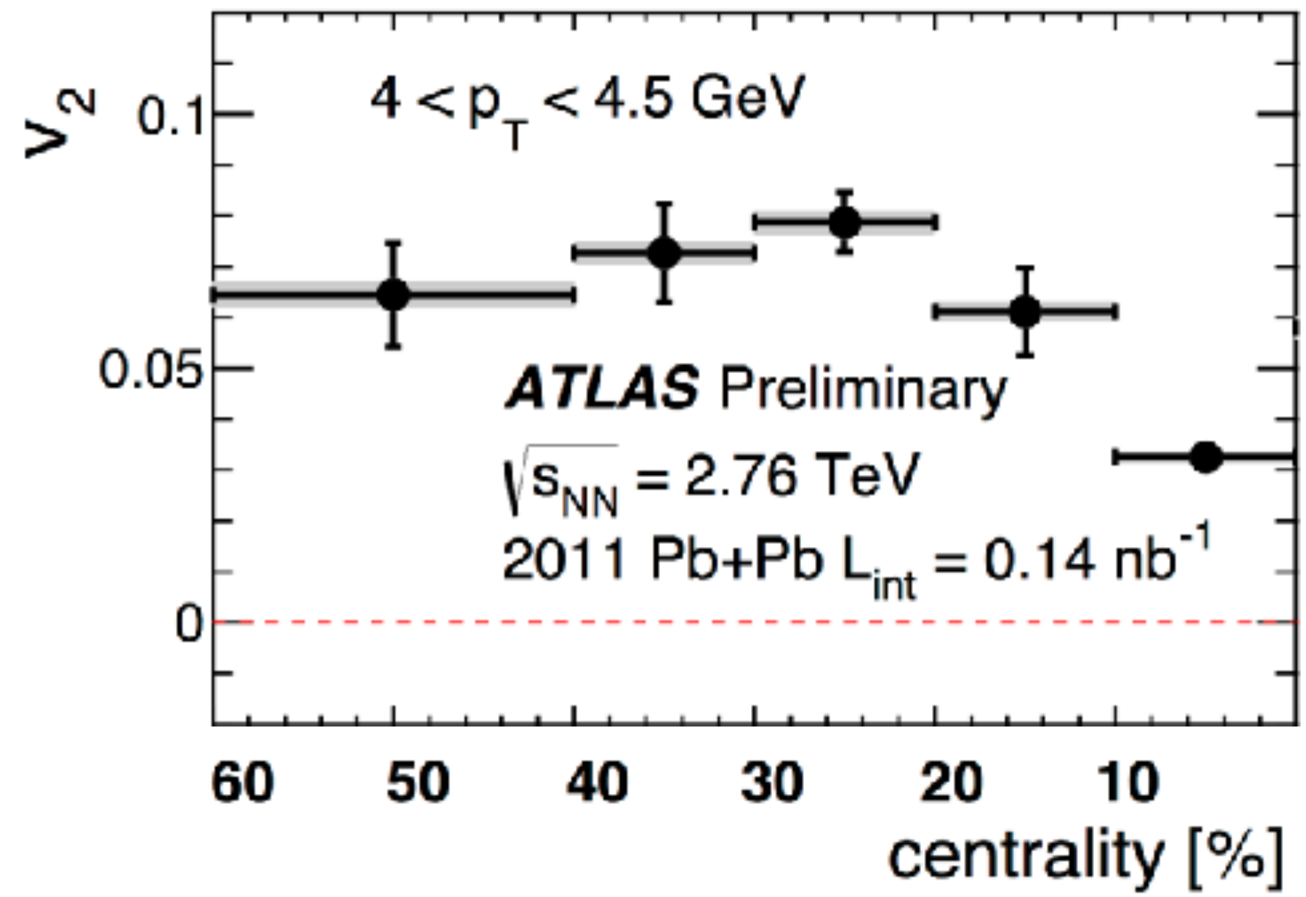




we need **charm quark diffusion** to describe the magnitude of the D meson v_2!

Heavy-flavour muons at 2.76 TeV



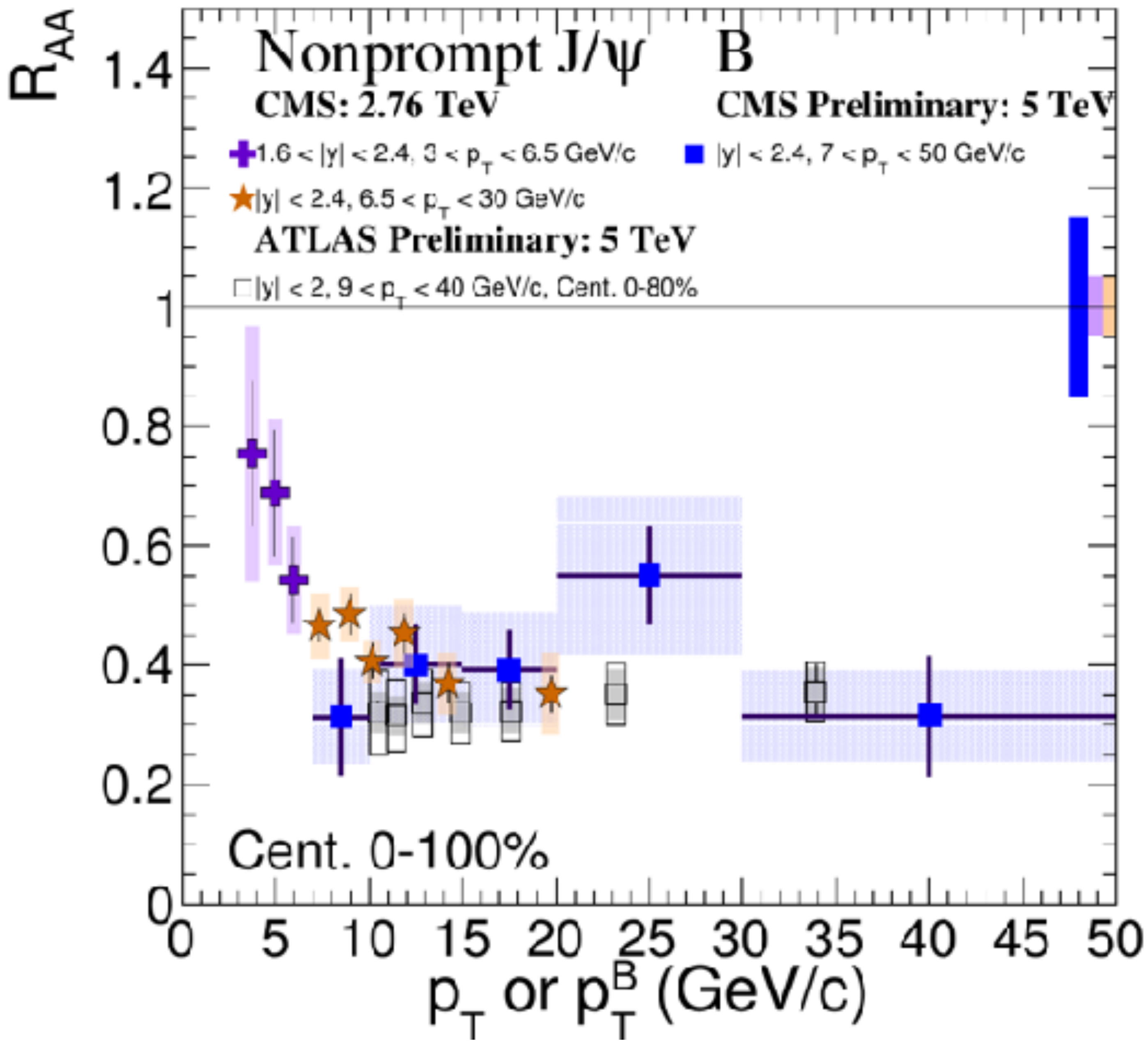


ATLAS-CONF-2015-053

Positive v_2 for muons from heavy-flavour decays (b+c) at LHC:

- include the contributions of beauty to v_2 that is currently unknown
- **v_2 of heavy flavour muons < v_2 (D^0) from ALICE**

Non-prompt J/φ at 2.76 TeV vs B$^+$ at 5.02 TeV



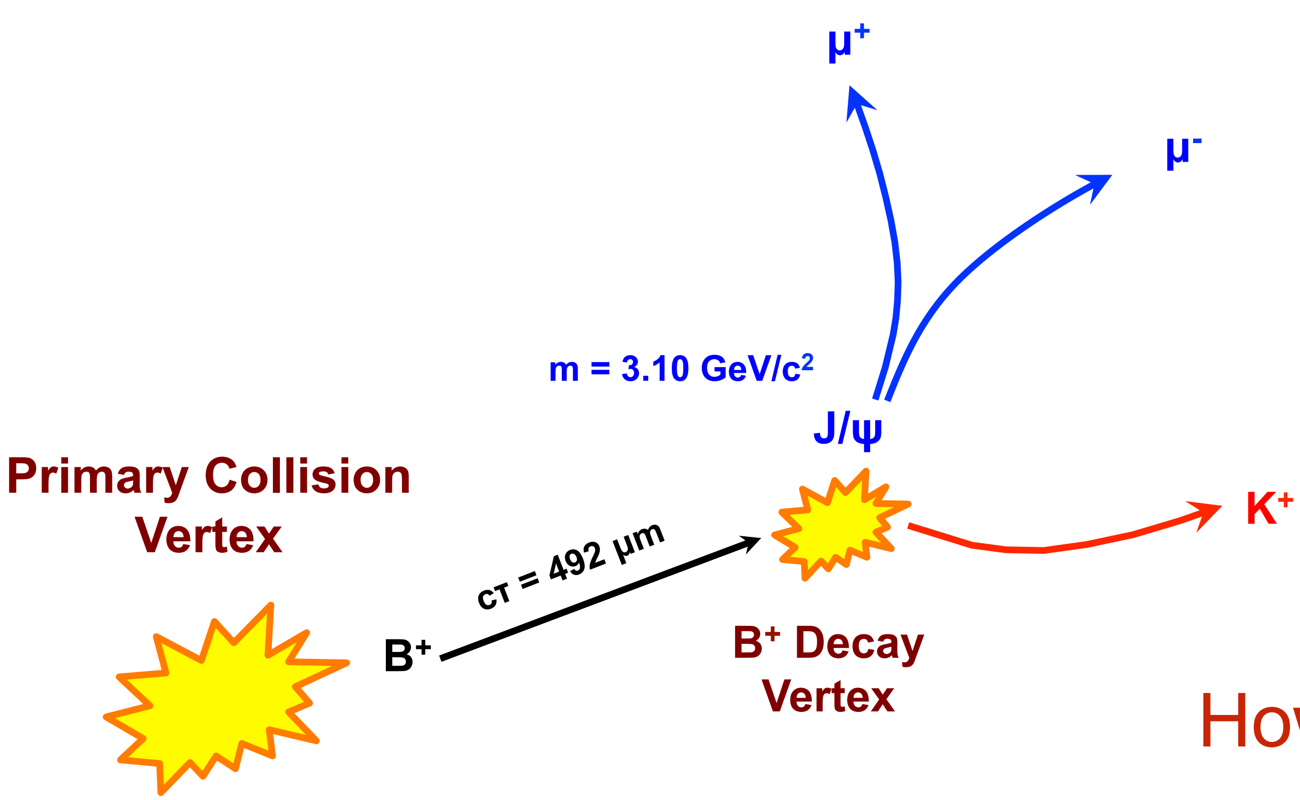
The B$^+$ R_{AA} at 5.02 TeV and non-prompt J/φ at 2.76 fully compatible within uncertainties!

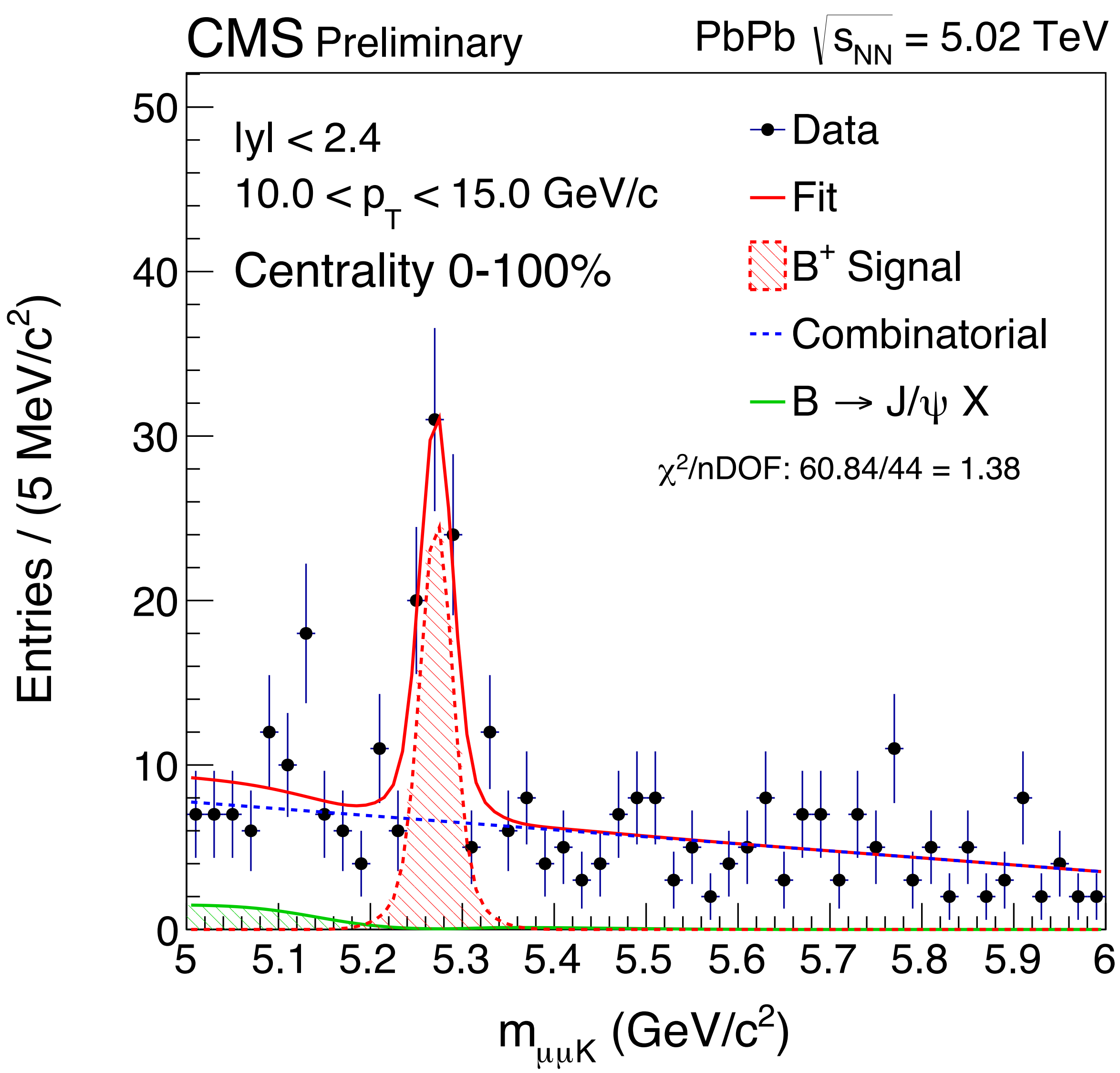
BIG CAVEAT: different energies!

Exclusive B-meson measurements

Exclusive B mesons can span the full range and get closer to the parton kinematic!

$B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+\mu^-\ K^+$



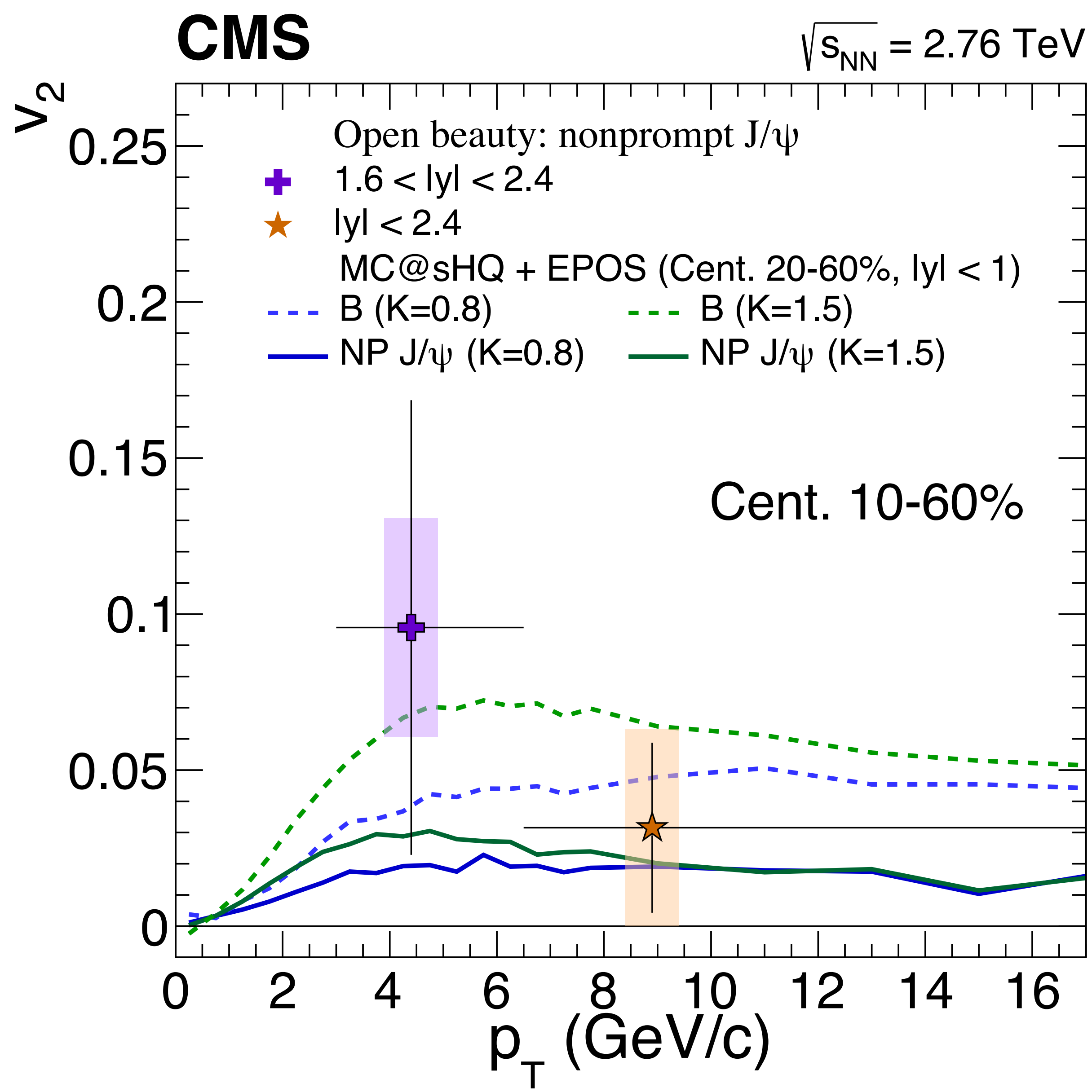


How do we reconstruct B mesons in CMS?

→ Clean and high statistics sample collected by triggering on muons!

v_2 of non prompt J/ψ

v_2 of non prompt J/ψ in PbPb collisions at 2.76 TeV



→Compatible within uncertainties with theoretical calculations

Looking to see the new measurement with Run2 data with higher statistics!

arXiv:1610.00613, Submitted to Eur. Phys. J. C

prompt and non prompt charmonia

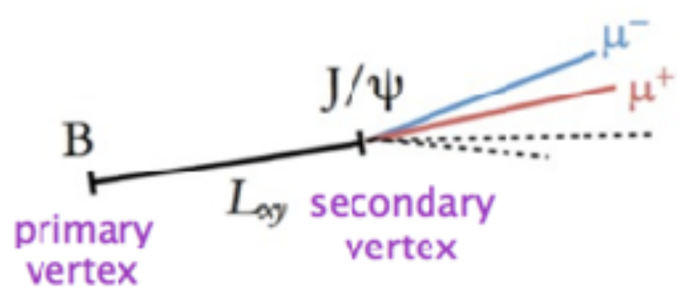
Inclusive J/ψ

- **Prompt J/ψ**
  - Direct J/ψ
  - Feed-down from ψ(2S) and χ_c
- **Nonprompt J/ψ** from B decays

- **Prompt component:**
  affected by color screening and regeneration in the QGP

- **Nonprompt component:**
  reflects E_{loss} of b quarks in the medium

Separation of components based on **pseudo-proper decay length** ($\ell_{J/\psi}$):



$$\ell^{3D}_{J/\psi} = L_{xyz} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$

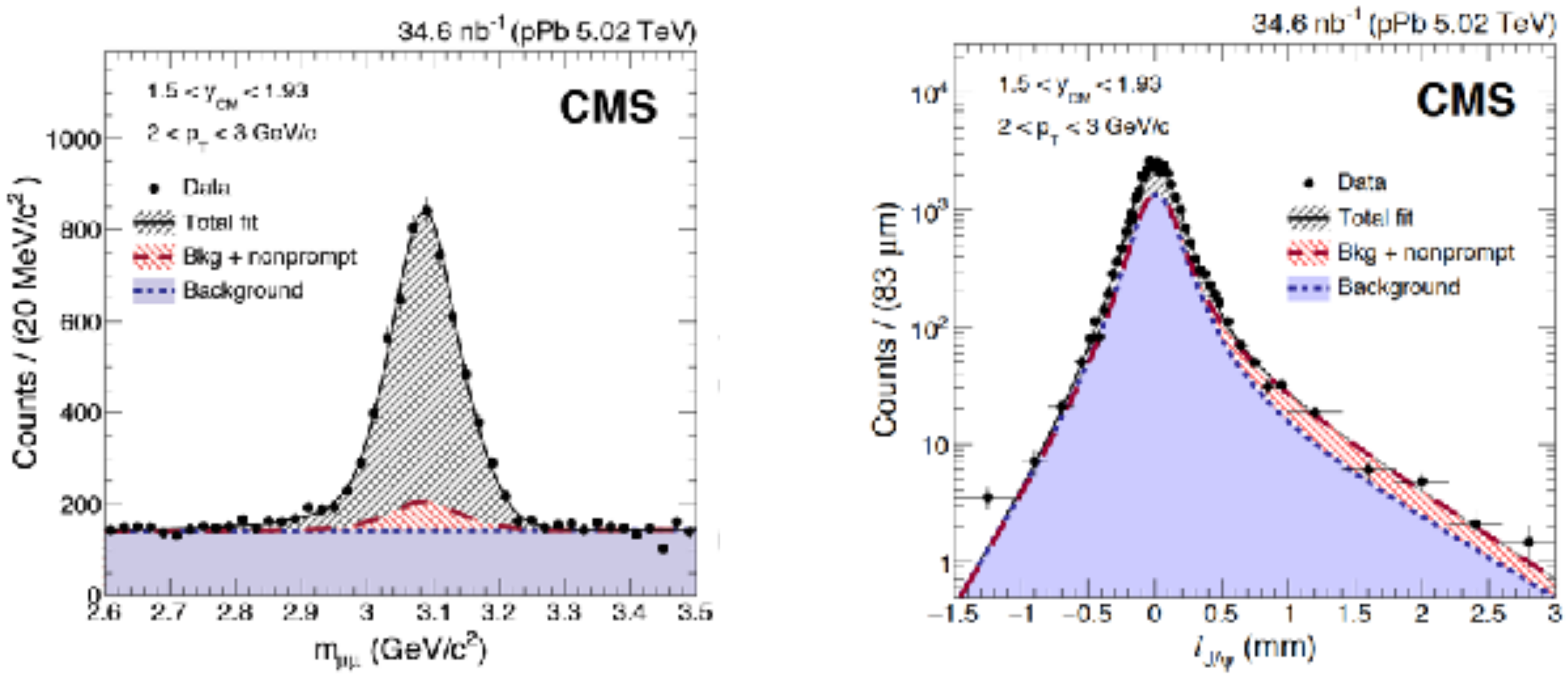
This talk:
prompt charmonia

Ta-Wei Wang's talk (8th):
nonprompt charmonia
& full B reconstruction

prompt and non prompt charmonia

Two techniques to separate components:

1. **2D fits of dimuon mass and pseudo-proper decay length**



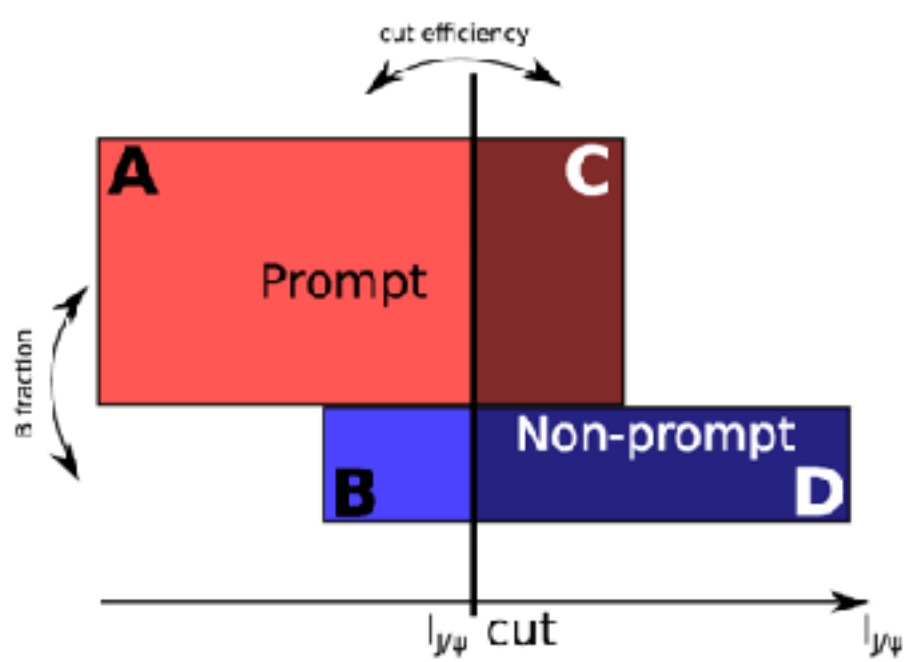
arXiv:1702.01462

2. **Rejecting nonprompt using a cut on $\ell_{J/\psi}$**

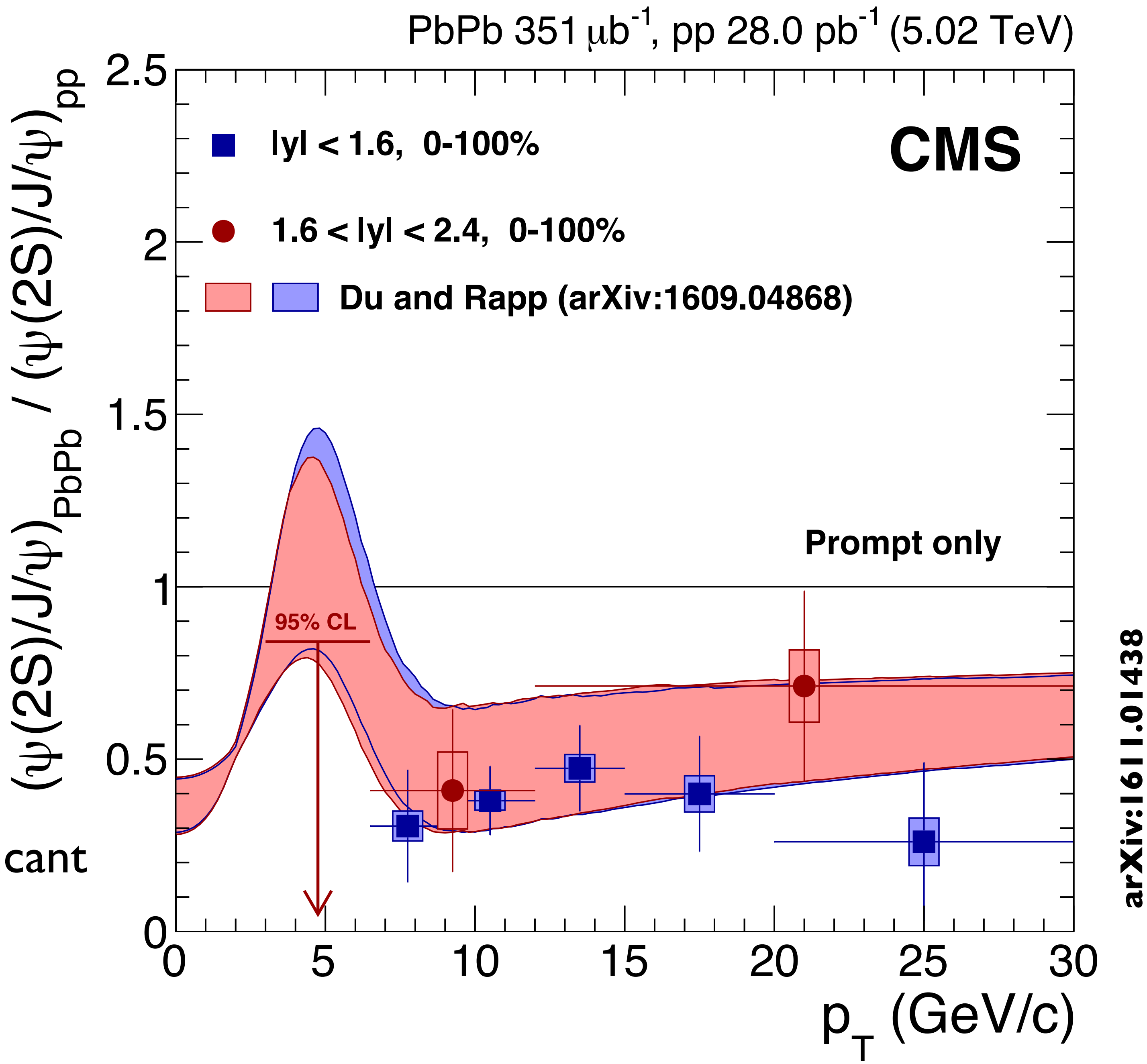
(can be used with low stats: ψ(2S) analyses)

Correction (from data) to account for remaining nonprompt contamination:

- Using reverted $\ell_{J/\psi}$ cut
- MC efficiency of $\ell_{J/\psi}$ cut



ψ(2S) /J/ψ vs p_T



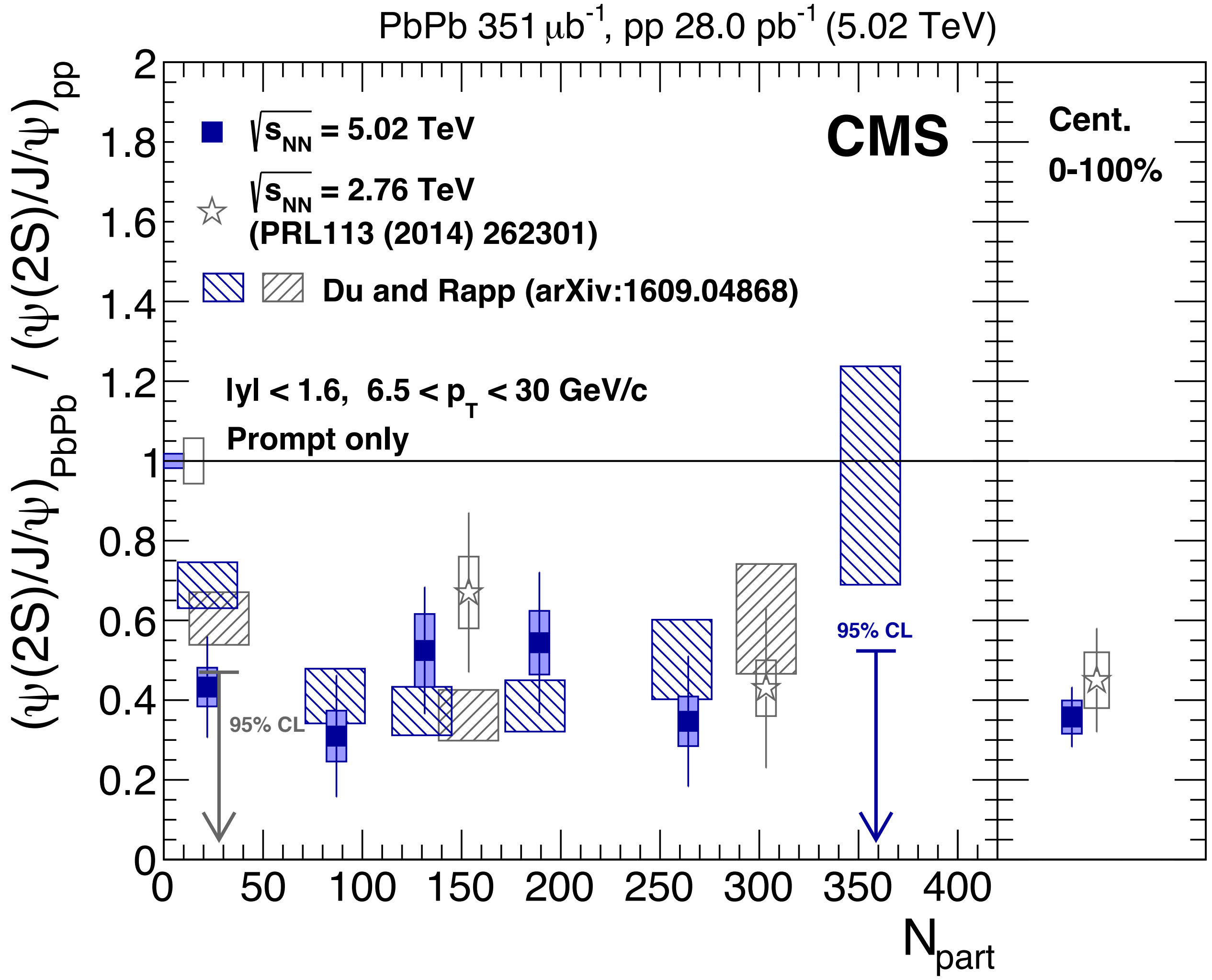
95% CL where no significant ψ(2S) signal in PbPb

- $R_{AA}(\psi(2S))/R_{AA}(J/\psi) < 1$ in all bins → **ψ(2S) is more suppressed than J/ψ**
- No p_T dependence within uncertainties
- X. Du and R. Rapp: transport model with temperature dependent reaction rates
  → ψ(2S) regenerated later than J/ψ in the fireball evolution?

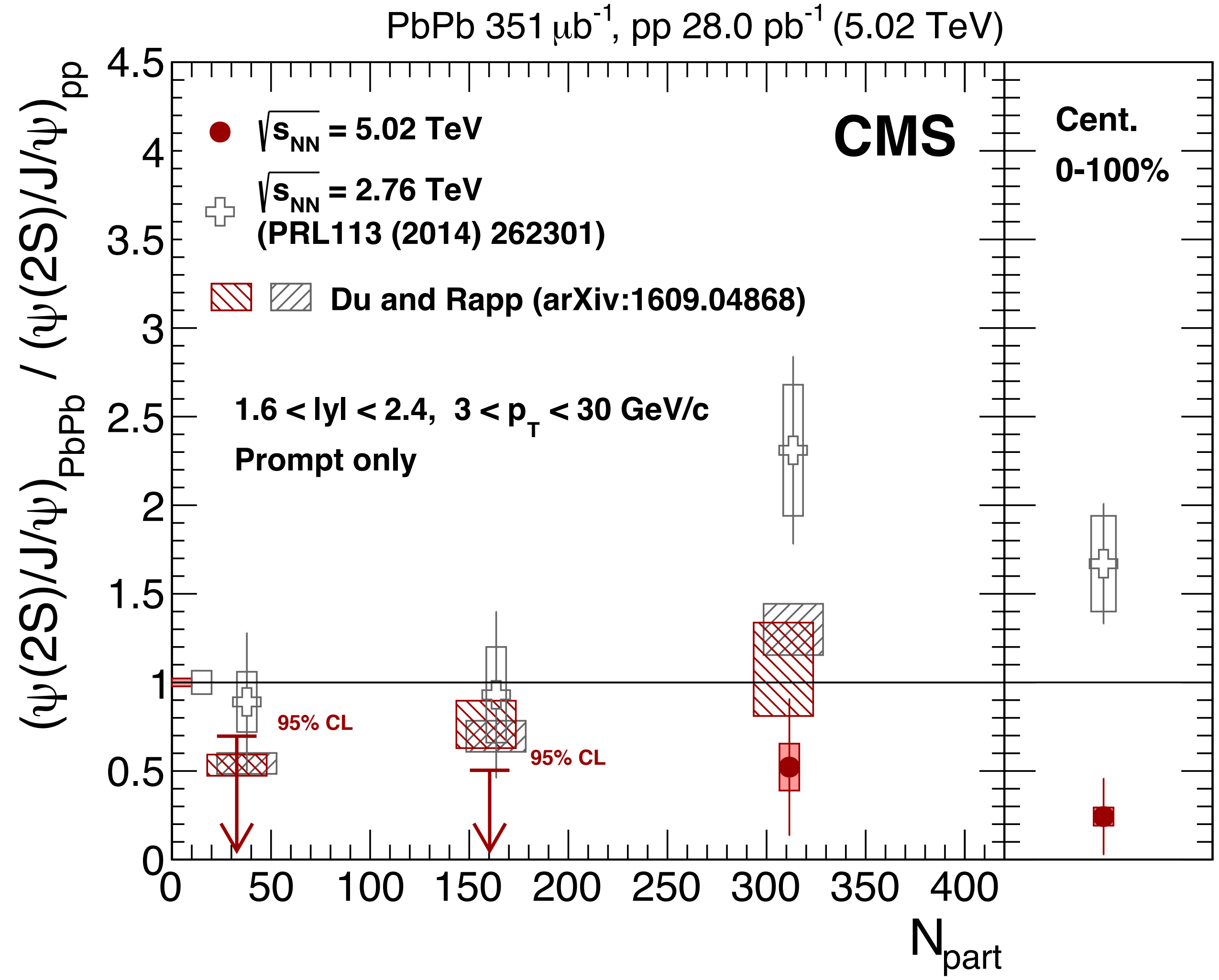
ψ(2S) /J/ψ vs centrality

2.76 vs. 5.02 TeV

$|y| < 1.6$; $6.5 < p_T < 10$ GeV/c



$1.2 < |y| < 2.4$;$3 < p_T < 30$ GeV/c

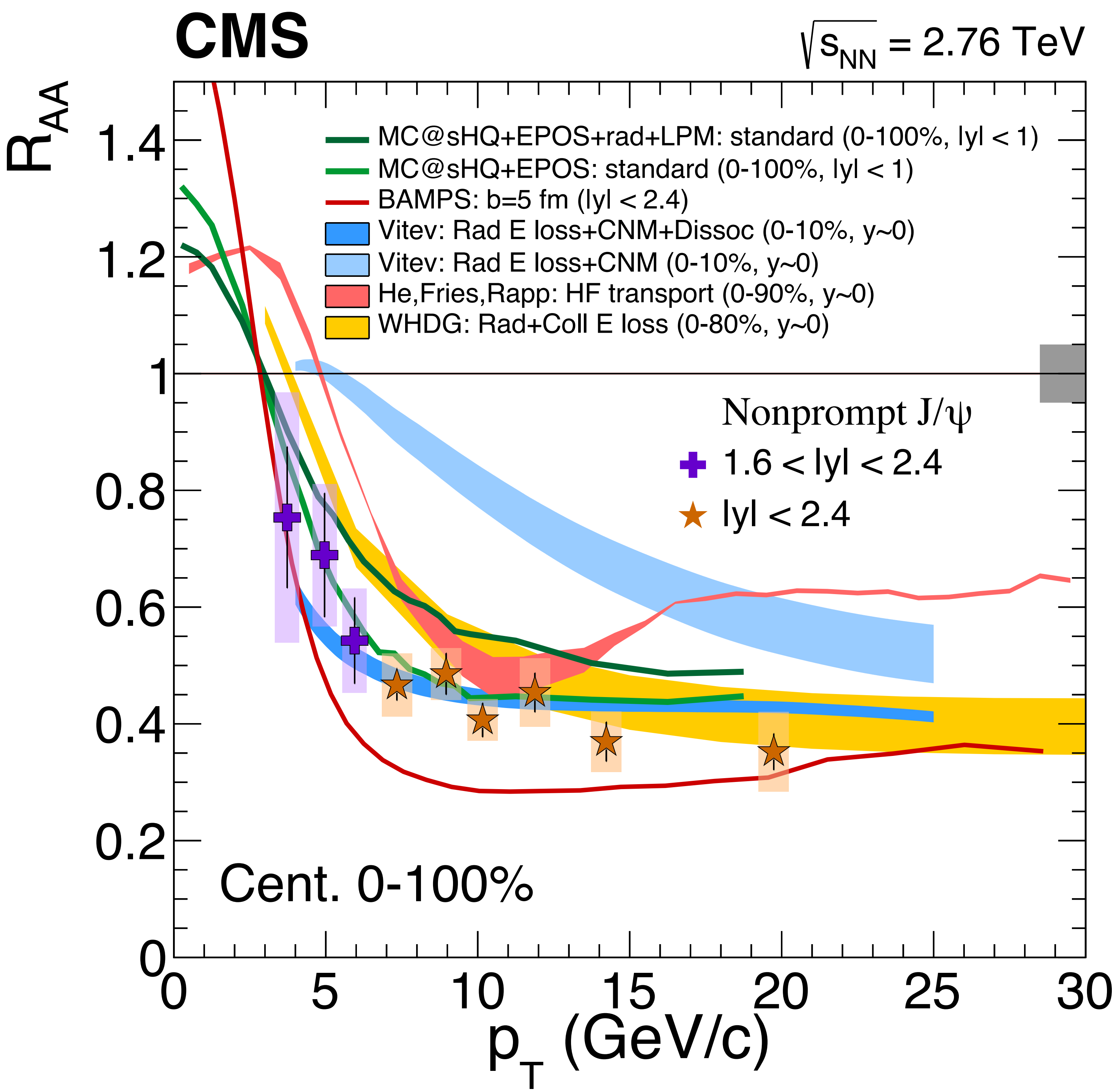


arXiv:1611.01438

CMS results vs centrality, p_T and rapidity can help to constrain the model:

- Relative contribution of primordial and regenerated charmonia
- Dissociation and regeneration rates
- Temperatures at which J/ψ and ψ(2S) regenerate
- …

Comparison to theoretical calculations



CMS non prompt 1.6<|y|<2.4

CMS non prompt |y|<2.4

arXiv:1610.00613, Submitted to Eur. Phys. J. C

Strong suppression observed for non prompt J/φ in PbPb collisions

Clear suppression as a function of p_T